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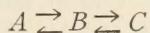
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THE NATURE OF LIGHT ACTION IN SELENIUM.

BY F. C. BROWN.

IN a paper by Brown and Stebbins¹ it was shown that the light-sensitivity of a certain selenium cell was a function of its resistance whether that resistance was conditioned by temperature, pressure, light or other agencies. This conclusion, together with the results of recent investigations, has led me to formulate an hypothesis for explaining the changes in the electrical conductivity occurring in light-sensitive selenium. The statement and the discussion of this hypothesis together with the results of investigations pertinent to this hypothesis will form the material of this paper. As the amount of data that must be correlated is quite large indeed, particular attention will be given only to the various effects produced by light.

The hypothesis is that all light-positive and light-negative varieties² of selenium consist of various mixtures of three kinds of selenium which we will call *A*, *B* and *C*, and that under the action of light *A* is changed into *B* and *B* is changed into *C*, according to the reaction,



and that the changes in both directions are proportional at all times to the amounts of the changing material. The principal argument that is offered for proposing such an explanation is that it seems to be consistent with the experimental facts under a variety of conditions, and that as is generally recognized previous theories do not explain many of the recently observed phenomena.

That the effect of illumination on certain varieties of light-positive selenium is to produce a genuine change in the selenium itself has not

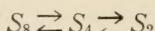
¹ PHYS. REV., 26, p. 273, 1908.

² For the meaning of this terminology see PHYS. REV., XXXII., p. 237, 1911.

been questioned since Pfund¹ and Berndt² showed that selenium cells made by using selenium of the highest purity and carbon electrodes were sensitive to light. By studying the conductivity at different temperatures Marc³ concluded that certain varieties of selenium consist of two allotropes *A* and *B* in equilibrium. Montén⁴ by observing the resistance in the dark at pressures between 0 and 3,000 atmospheres concluded that the selenium cells that he used consisted of at least two allotropes *A* and *B* in equilibrium under the given pressures.

More recently Kruyt⁵ has made density measurements that indicate that in light-sensitive selenium there are two components that are in equilibrium according to the reaction $A \rightleftharpoons B$.

This paper will not attempt to define the three components whose existence is supposed nor will it consider the particular reasons why the components have different rates of change under the same external conditions. But since Blitz and Preuneur⁶ have found three components in sulphur changing under the influence of pressure and temperature according to the reaction



it would not be surprising to find later that the three components of light-sensitive selenium may be identified and studied as separate allotrophic forms.

THEORY.

In order to obtain conditions which are easily subject to theoretical treatment we will suppose that the sensitive layer of selenium may be so thin that the impinging light may be of practically uniform intensity throughout the layer, and that temperature, pressure and all other conditions except that of illumination that affect the conductivity remain constant; further suppose that the conductivity of the *A* kind is zero, while that of the *B* kind approaches that of the metals and that the conductivity of the *C* kind is so much smaller than that of the *B* kind that it may be neglected. Part of the experimental evidence in favor of neglecting the conductivity of the *C* kind will be brought out in this paper but the most direct evidence will be presented in a later paper concerning the recovery of selenium. Let α_1 and β_1 be the respective rates of change of *A* into *B* and *B* into *C* for a given set of conditions and α_2 and β_2 the

¹Phil. Mag., 7, p. 26, 1904.

²Phys. Zeit., 5, p. 121, 1904.

³Zeit. anorg. Chem., 48, p. 5, 1906.

⁴Archiv. für Matematik, Astronomi och Fysik, 4, p. 1, 1908, also dissertation on "The Influence of Pressure on the Electrical Resistance of Selenium and Silver Sulphide."

⁵Zeit. für anorg. Chemie, 64, p. 305.

⁶Zeit. Phys. Chem., 39, p. 323.

corresponding reverse changes of C into B and of B into A . Let A_0 , B_0 and C_0 represent the initial amounts of the respective kinds before illumination. By illumination the constants α_1 and β_1 increase in value and are probably accompanied by small changes in α_2 and β_2 , so that after a time t_1 , the respective amounts of the three kinds are A_1 , B_1 and C_1 . Nothing will be said concerning the homogeneity and uniformity further than that the way in which the three components are mixed shall not to any great extent affect the following expression for the conductivity,

$$i = K_1 B. \quad (1)$$

Then the changes take place in accordance with the following equations:

$$dA/dt = \alpha_2 B - \alpha_1 A, \quad (2)$$

$$dB/dt = \alpha_1 A - \alpha_2 B + \beta_2 C - \beta_1 B, \quad (3)$$

$$dC/dt = \beta_1 B - \beta_2 C, \quad (4)$$

$$A + B + C = K, \quad (5)$$

$$dA/dt + dB/dt + dC/dt = 0. \quad (6)$$

From these equations we obtain the differential equation,

$$[\ddot{B}] + (\mu + \alpha_1)[\dot{B}] + (\alpha_1\mu - \alpha_2\lambda)B - \beta_2\alpha_1 K = 0, \quad (7)$$

where

$$(\alpha_1 - \beta_1) = \lambda,$$

$$\alpha_2 + \beta_2 + \beta_1 = \mu.$$

This equation is of the form,

$$[\ddot{B}] + M[\dot{B}] + NB - L = 0.$$

The solution of the equation is

$$B = L/N + c_1 e^{+m_1 t} + c_2 e^{m_2 t}, \quad (8)$$

and

$$C = \frac{L\beta_1}{N\beta_2} + \frac{\beta_1 c_1 e^{m_1 t}}{\beta_2 + m_1} + \frac{\beta_1}{\beta_2 + m_2} c_2 e^{m_2 t}, \quad (9)$$

where

$$L = \alpha_1 \beta_2 K, \quad (10)$$

$$N = \alpha_1 \beta_1 + \alpha_1 \beta_2 + \alpha_2 \beta_2, \quad (11)$$

$$m_1 m_2 = \alpha_1 \beta_1 + \alpha_1 \beta_2 + \alpha_2 \beta_2, \quad (12)$$

$$m_1 + m_2 = -(\alpha_1 + \alpha_2 + \beta_1 + \beta_2), \quad (13)$$

$$B_0 = L/N + c_1 + c_2, \quad (14)$$

$$C_0 = L/N \times \beta_1/\beta_2, \quad (15)$$

for equilibrium in the light,

$$B_1 = \frac{L}{N} = \frac{(\alpha_1 \beta_2)K}{\alpha_1 \beta_1 + \alpha_1 \beta_2 + \alpha_2 \beta_2}, \quad (16)$$

$$C_1 = \frac{L}{N} \times \frac{\beta_1}{\beta_2} + \frac{\beta_1}{\beta_2 + m_1} c_1 + \frac{\beta_1 c_2}{\beta_2 + m_2}, \quad (17)$$

$$\frac{\alpha_2}{\alpha_1} B_1 + B_1 + \frac{\beta_1}{\beta_2} B_1 = K, \quad (18)$$

and the value of the constants in equation (8) are

$$c_1 = \left[\frac{C_0}{\beta_1} + \left(\frac{L}{N} - B_0 \right) \frac{1}{\beta_2 + m_2} - \frac{L}{N \beta_2} \right] \left[\frac{(\beta_2 + m_2)(\beta_2 + m_1)}{m_2 - m_1} \right], \quad (19)$$

$$c_2 = \left[\frac{C_0}{\beta_1} + \left(\frac{L}{N} - B_0 \right) \frac{1}{\beta_2 + m_1} - \frac{L}{N \beta_2} \right] \left[\frac{(\beta_2 + m_2)(\beta_2 + m_1)}{m_1 - m_2} \right]. \quad (20)$$

Since the conductivity depends only on the amount of the *B* kind present, our problem is to determine how the amount of the *B* kind should

TABLE I.

Case.	1	2	3	4	5
After illumination					
$\begin{cases} a_1 \\ a_2 \\ \beta_1 \\ \beta_2 \end{cases}$.13 10. 2.66 .05	.13 10. 2.66 .05	.03 .40 .40 .3	10 .13 2.66 .05	10 .13 2.66 .05
m_1	-10.39	-10.39	-.7	- 2.65	- 2.65
m_2	-.058	-.058	-.2	-10.19	-10.19
A_0	14,890.	121,000.	290.	12,880.	2,220.
B_0	1.0	1.0	10.	10,000.	10,000.
C_0	1.0	10,000.	10.	85,120.	95,760.
A_1	9,320.	77,000.	265.	30.	30.
B_1	120.	1,000.	20.	2,000.	2,000.
C_1	6,360.	53,000.	25.	106,000.	106,000.
K	15,900.	131,000.	310.	108,000.	108,000.
L/N	120.	1,000.	20.	2,000.	2,000.
Per cent. A_0	90.	92.	90.	12.	2.
Per cent. B_0	.06	.008	3.2	9.0	9.0
Per cent. C_0	10.	8.	7.	79.	89.0
Before exposure	$\begin{cases} a_1/a_2 \\ \beta_1/\beta_2 \end{cases}$	$.67 \times 10^{-4}$	8×10^{-5}	.035	.8
					5.0
After exposure	$\begin{cases} a_1/a_2 \\ \beta_1/\beta_2 \end{cases}$	1.0	10^3	1.0	8.5
					9.5

vary with the time of illumination, as specified in equation (8), when different initial conditions are considered. To do this we must first determine the constants m_1 and m_2 and c_1 , c_2 and L/N . These constants depend on the rates of change and the initial amounts of the *A*, *B*

and C components. The rates of change must be positive quantities under all conditions. In accordance with equations (12) and (13) this obviously requires that m_1 and m_2 shall always be of negative sign. Also the amount of the three components A , B and C must necessarily be positive quantities, and it seems reasonable to expect that the ratios α_1/α_2 and β_1/β_2 should always be increased by the action of light. This last presumption would further require that during illumination the amount of the C kind must always be increased and that at the same time the A kind must be decreasing. The B kind may obviously either increase or decrease depending upon the relative amounts of change in the A and C kinds. These are all the conditions that it seems wise to impose at present. Further experimentation may show that not only do the rates of change vary according to simple laws with changes in the intensity but that the ratios of the rates also vary according to correspondingly simple laws.

By a method of approximations and guesses I have found specimen arbitrary values for the rates of change, which when taken with appropriate values of the other constants will establish the characteristic ways in which the conductivity, i , will vary with the time of exposure to light. All the constants must be in harmony with the twenty equations given and also must satisfy the other necessary conditions. The equation as obtained from (1) and (8) shows the relation between the conductivity and the time of exposure to be

$$i = K_1(L/N + c_1e^{m_1 t} + c_2e^{m_2 t}). \quad (21)$$

Certain values of the constants and other information is given in the accompanying Table I. This table furnishes the values for the constants in the above equation, the graphs of which are shown in Fig. 1. The equations of the curves are as follows;

$$\begin{aligned} \text{curve 1, } B &= 120 - 138e^{-10.39t} + 19e^{-0.058t}, \\ \text{curve 2, } B &= 1000 - 1160e^{-10.39t} + 160e^{-0.058t}, \\ \text{curve 3, } B &= 20 - 4.872e^{-.7t} - 5.12e^{-2t}, \\ \text{curve 4, } B &= 2000 - 3250e^{-10.59t} + 11250e^{-2.65t}, \\ \text{curve 5, } B &= 2000 + 5670e^{-2.65} + 2340e^{-10.59t}. \end{aligned}$$

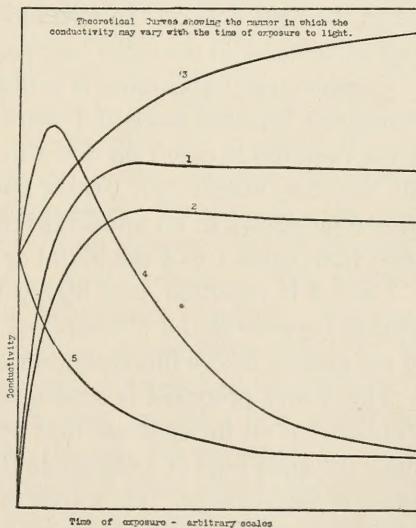


Fig. 1.

The main points that are essential to the theory may be understood most easily by studying the curves. In (1) and (2) the initial conductivity is very small and it rises rapidly to a maximum and then falls off slowly to a constant limiting value. The equilibrium value of the conductivity in the light to that in the dark is of the ratio 1,000 to 1. Curve (3) shows the conductivity in the dark to be greater than that shown in (1) and (2). The increase of conductivity due to illumination is always positive. It increases most rapidly at first. In the fourth case the conductivity rises rapidly by illumination to a maximum, that is, relatively to the initial conductivity not very large and then falls off quite rapidly to a value which may be even less than the initial conductivity. Curve (4) shows the manner of variation although it does not show the fact that the initial conductivity is much larger than prevails in the first three cases.

In what is called case 5 the conductivity begins to decrease at once when the light acts on the selenium and it falls rapidly compared to the rate of decrease in the other four cases noted.

Considerable importance is attached to the fact that the decrease of resistance becomes more and more rapid as the conditions change from those required in case 1 on down to those required by case 5, and that in all the cases except No. 5 there are changes in the conductivity in both directions shown in an unmistakable manner; also to the fact that as we shift from cases 1 to 5 the initial or dark conductivity increases.

Case 2 is regarded as a highly improbable one in that the rates of change between *B* and *C* compared to the reverse changes between *C* and *B* are greater before illumination than afterwards.

The theory proposed is simple and attractive in so much as it rather implies that all the agencies that affect the conductivity of selenium produce the same kind of a change in the selenium, namely a variation in the rates of interchange. Or stated in other words the selenium is in equilibrium under a variety of conditions. Each agency merely acts in a way to alter the equilibrium by changing the rates. Whether or not every agency changes the rates in accordance with the same laws after the units have been properly adjusted is a matter that will have to be determined by experiment. Any variety of selenium which shows a marked increase of conductivity at first and then is followed by a decrease when acted on by light should in all probability show the same two changes when acted on by other agencies, but this conclusion is clearly not required. For example, a Giltay or a high sensibility selenium cell which by illumination rises to a maximum conductivity, say 100 times as great haste conductivity in the dark, and then falls to only 30 times the

dark conductivity, might reasonably be expected to rise to the same maximum and then to fall to the same limiting value 30 to 1, if there were a sudden application of mechanical pressure of the right amount. The same argument would apply to the agencies of temperature and differences of electric potential.

A mechanical interpretation of the theory may be proposed as follows: The *A*, *B* and *C* varieties because of their rates of interchange are in equilibrium. When the selenium is illuminated new rates are established and consequently new equilibrium values for the amounts of the *A*, *B* and *C* kinds. We may regard the selenium as distorted from its equilibrium condition, and the study of the change of conductivity as merely a study of one of the processes taking place while the new equilibrium is being established. In fact experiment shows that it is possible to distort the selenium system, if it may be called such, so that the amount of any kind may be either greater or less than is required for equilibrium. So far as the *B* kind is concerned the distortion may be either positive or negative in at least one variety of selenium, while the condition of light or darkness is changing in only one direction. Or suppose any variety of selenium in equilibrium in the diffuse light of a room; the selenium may be distorted in one direction by imposing the condition of darkness. It may be distorted in the opposite direction by imposing the condition of intense illumination. By increasing the intensity of illumination the amount of the *C* kind increases and by decreasing the illumination the amount of the *C* kind decreases. The following argument will illustrate what general behavior is expected. Suppose a selenium cell in equilibrium in the dark in a condition which we will call ϕ . Next expose it to intense light and as a result of the existing distortion it changes according to certain laws toward a new equilibrium condition which we may call θ . The changes can be shown by curves. Finally remove the selenium to the dark and again due to the distorted condition of the selenium it will return to its former dark condition ϕ . The changes from θ to ϕ can also be represented on curves. The general movement of the change in the first case may be said to be in the positive direction and in the second case it may be said to be in the negative direction. The changes in the negative direction as shown by the second set of curves may be said to be the reciprocal of the changes in the positive direction and the time taken for the selenium to go from θ to ϕ should be of the same order of magnitude as the time required for the selenium to go from ϕ to θ . Where there is a rapid change and a slow change going in one direction there should in general be both the rapid and the slow changes in the reverse process.

In a recent paper¹ given before the American Physical Society was developed an equation for the conductivity on the assumption that the reverse changes α_2 and β_2 were at all times small compared to the direct changes, and that the conductivity of the C kind was one half as large as that of the B kind. It was stated that these assumptions were only tentative. As certain facts are brought out both by the agreement and by the disagreement of the experimental results with the equation developed,

$$i = k_1 \left\{ \frac{A_0 \alpha_1}{\alpha_1 - \beta_1} (e^{-\beta_1 t} - e^{-\alpha_1 t}) + B_0 e^{-\beta_1 t} \right\} + k_2 \left\{ \frac{A_0}{\alpha_1 - \beta_1} [\alpha (1 - e^{-\beta_1 t}) - \beta (1 - e^{-\alpha_1 t})] + B_0 (1 - e^{-\beta_1 t}) + C_0 \right\}$$

two families of curves taken from this equation are shown in Fig. 2 and Fig. 3. The theoretical objection that is urged against these

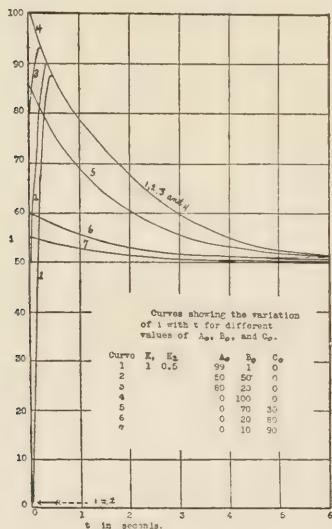


Fig. 2.

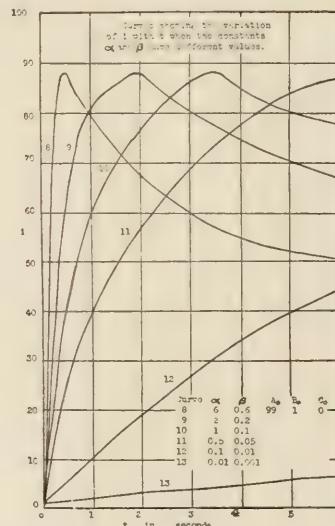


Fig. 3.

special assumptions is that there is no method of accounting for the initial amounts of the three kinds in the dark, and consequently no satisfactory way of explaining the recovery of the selenium after the light is removed. Wherein the experimental results show that the special assumptions are not warranted will be brought out in the discussion of the results.

¹ PHYS. REV., Vol. XXXII., p. 237, 1911.

GENERAL CONSIDERATIONS.

Some time ago I observed a striking relation between the resistance of selenium and its sensibility to light. In this instance, sensibility is used in the sense of the ratio of the conductivity in the light to the conductivity in the dark, when the selenium was exposed directly to sunlight or its equivalent for about 5 minutes. The relation observed was that the higher the resistance the greater was the sensibility or conversely the lower the resistance the less the sensibility and finally when the resistance became very low the sensibility became of the negative sign. The accompanying Table II. shows the observations that were made. However it must be remembered that the values represent only orders of magnitude. The specific resistance is not in all cases proportional to the measured resistance of the selenium. Further as the sensibility was measured without any intention of making such comparisons as here noted, the sensibility also is subject to a large error. Nevertheless the relation mentioned is very clearly shown.

TABLE II.

Kind of Selenium.	Resistance.	Sensibility.
High sensibility selenium cell,	10^9	200 to 1
Giltay selenium cell,	400,000	30 to 1
Ruhmer selenium cell,	90,000	10 to 1
Home made, 1904,	100,000	10 to 1
Home made, 1904	160,000	4 to 1
Home made, 1904,	30,000	2 to 1
Home made, 1904,	17,000	1.1 to 1
Home made, 1904,	12,000	1.0 to 1
Home made, 1904,	3,500	1.0 to 1
Light negative selenium,	400	-1.002 to 1
Light negative selenium,	20	-1.15 to 1
Light negative selenium,	1	-1.5 to 1

Since making these observations I have learned that Pochettino and Trabacchi¹ and also J. W. Giltay have made observations that show this same relation existing between resistance and sensibility. Giltay in one of his trade circulars on selenium cells, says that he makes high resistance selenium cells of high sensibility and low resistance selenium cells of low sensibility and adds that "low resistance and high sensibility simply do not go together."

As an example of diverse facts concerning selenium, which do not seem to any conclusion we may note the laws of change of conductivity with light intensity as given in Table III., where m represents the

¹According to Ries in his book on Die Elektrischen Eigenschaften und die Bedeutung des Selens für die Electrotechnik.

change of conductivity, i represents the light intensity, R the resistance, and the other quantities constants.

TABLE III.

Law.	Authority.
$i = cm^2$	Rosse, Adams, Berndt.
$i = cm^3$	Hopius.
$i = m(m-a)b$	Athanasiadis.
$i = b^m - 1$	Hesenus.
$R_a/R_b = (b/a)^a$	Ruhmer.
$I = cm$	Stebbins. ¹

Without doubt all the variations in the results of the above investigators can be explained on the ground that the conditions were widely different in many cases. The varieties of selenium were not the same; the intensity ranged between different limits; and no doubt the time of exposure was different in each case. Other legitimate reasons might be sought for in the construction of the cell form and the thickness of the selenium on this form. The facts in this table are presented merely to demonstrate the futility of search for a simple universal law connecting the conductivity of a selenium cell and the intensity of illumination. It is obviously necessary to look to other relationships than the one mentioned if we wish to connect the facts by simple laws.

The properties of the known varieties of selenium are summed up in Table IV., so far as information has been obtained. The purpose here is to call attention in a more general way more particularly to the diverse properties of selenium.

TABLE IV.

Variety of Selenium.	Change of Conduc- tivity by Light.	Conduc- tivity in the Dark.	Direction of Change of Con- ductivity.			
			By Tem- pera- tures.	By Pres- sure.	By Elec- trical Diff. Poten- tial.	By Mois- ture.
High sensibility cell	+ followed by -	10^{-9}	-	?	+	+
Giltay cell	+ followed by -	10^{-6}	+	+	+	?
Ruhmer cell	+	10^{-5}	+	+	+	+
Ries's "abnormal cell"	+ followed by -	?	?	?	?	+
Light-negative cell	-	10^{-2}	+	?	+ or -	-

It is not certain how many of these diverse properties may be in part due to impurities in the selenium. Also we are very much in doubt as

¹ Proved by Stebbins for faint illumination by two independent methods in connection with his work on the Measurement of the Light of Stars by a Selenium Photometer, in *Astro-Phys. Jour.*, 32, p. 185, 1910. However his results are not published.

to what is the depth of penetration of selenium by light. Before the proposed theory can be put to a rigid test it will be necessary to answer the last question but not the first. But this question cannot be answered at present. We may now proceed to call attention to experiments with the above varieties of selenium.

EXPERIMENTS WITH LIGHT-POSITIVE SELENIUM.

In most of the experiments with light-positive selenium, a selenium cell designated Giltay No. 2, which was made by Giltay of Delft, Holland, was used. For somewhat more than a year previous to its use for the experiments described in this paper it has been left in paraffin oil in a glass tube of about 4.5 cm. diameter and 25 cm. length. With the exception of a space left for a window, the tube had been black enameled on the exterior surface. This tube was surrounded by a second similar tube. When the second tube was so turned that the two windows were together, the cell could be illuminated. The temperature of the oil in which the cell was placed was read from a thermometer projecting through a rubber cork down into the oil. In the dark at 25° C. the cell had a resistance of about 490,000 ohms.

Whenever changes in the conductivity were investigated that occurred during short intervals of time, a pendulum and a ballistic galvanometer were used in connection with a Wheatstone's bridge circuit. This method of measuring such changes of resistance is discussed elsewhere.¹ It will be sufficient to state here that the average conductivity of the selenium during any interval is a function of the deflection of the galvanometer, which function can be determined either by experiment or calculation. The method of illumination was to place a tungsten lamp in the same dark box in which the selenium cell was placed and to regulate the time of illumination by opening and closing keys controlling the current through the lamp. If the period of illumination desired was a fraction of a second, the keys were manipulated entirely by the pendulum which threw in the ballistic galvanometer. It was assumed that the light reached a constant value at once and no correction was made for the fact that the candle-power of a tungsten lamp decreases perceptibly after the current is turned on.

The change of conductivity varies with the time of illumination. In all high sensibility selenium cells the conductivity first rises rapidly to a maximum and then it falls off fairly rapidly at first and then more slowly. This is shown for the Giltay No. 2 in curve 14 of Fig. 4, where the cell was exposed to a 16-cp. lamp at about a distance of a meter.

¹See paper by Brown and Clark, *PHYS. REV.*, 1911.

The maximum conductivity is reached in about 50 sec. and is about seven times greater than the conductivity in the dark. In curve 15 is shown the variation of conductivity with time for a very intense illumination. The intensity was approximately that of a 32-cp. lamp at a distance of 7 cm. It will be noted that the maximum conductivity is reached in .35 sec.

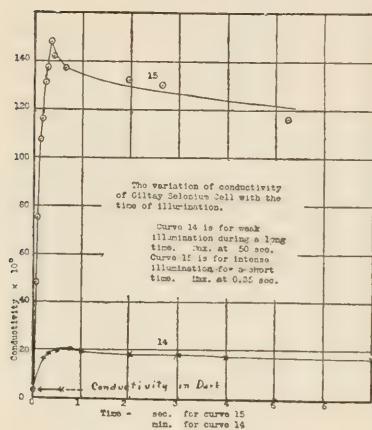


Fig. 4.

There are three sources of error in obtaining these observations which for our present considerations are of minor importance. The first arises from the fact that the intensity of illumination of a tungsten lamp does not become constant at once when the current is turned on. The second error was in the current itself. The storage battery used did not

TABLE V.

Observations on the Change of Conductivity of Selenium Cell Giltay No. 2 with Time by Use of Pendulum and Ballistic Galvanometer.

Temp.	Resistance in Dark.	Distance Apart of Second and Third Keys.	Time of Exposure.	Mean Cor- rected Time.	Deflection.	Conductivity $\times 10^6$.
28° C.	370,000	.1 sec.	0	0	0	2.7
			0.1 sec.	0.050	28	48
			.05	0.075	35	75
			.05	0.125	41	107
			.05	0.175	45.5	116
			.05	0.225	50.8	131
			.05	0.275	52.5	137
			.05	0.325	56.5	148
			.05	0.375	52.5	137
			.05	0.375	53.1	141
			.05	0.625	52.4	137
			.05	2.65	48.9	130
			.05	2.0	48.1	129
			.05	5.25	45.0	115
			.05	9.4	41.	107

furnish an unvarying E.M.F. After a few seconds use there was observed several times a slight decrease in the current. If however the lamp was connected in the regular lighting circuit substantially the same results were obtained as when the storage battery was used. The third error arose from incomplete recovery between readings. Practically from 1 minute to 1 hour was considered sufficient time, the time depending upon the intensity and duration of exposure and the temperature. For reasons which will be given later, we shall see that the reaching of the initial dark resistance does not necessarily require that the equilibrium condition shall be reached for a particular temperature or light condition. But equilibrium does require a particular resistance, under given conditions.

The amount of the decrease of conductivity in the Giltay cell is by no means pictured in curve 15. Other sets of observations were made where the time of illumination extended over a period of 15 minutes, *i. e.*, about one hundred and fifty times as long as in the instance just discussed. A Siemens and Halske needle galvanometer was placed in series with the cell and the conductivity was determined directly from the readings. The intensity of illumination was approximately the same as that for the short exposure. The decrease of the conductivity was extremely large as will be readily seen by referring to curves 16 and 17 of Fig. 5. In these cases the maximum conductivity was probably reached in 0.4 sec. At the temperature of 17° C. the conductivity was of the order of one hundred times that of the conductivity in the dark and at 41° C., the maximum ratio of the two conductivities was about 30 to 1. It may be observed from the curves that these ratios decreased after 10 minute exposures to 60 to 1 and 12 to 1. These last ratios probably represent very nearly the condition of equilibrium with the given intensity of light compared with equilibrium in the dark for the two temperatures stated. It is significant however that the equilibrium is approached with equilibrium in the dark for the two temperatures decidedly more rapidly at the higher temperature. The first deflection of 40 recorded in curve 17 is no doubt somewhat too high, due to the inertia of the galvanometer needle system.

The remarkable decrease in the conductivity of the Giltay cell is just as remarkable as is the enormous increase at first. Certainly it is of just

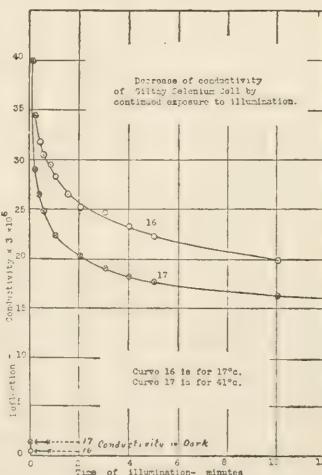


Fig. 5.

as much importance theoretically. First of all it is quite necessary to know if this decrease in the conductivity represents a genuine change in the selenium or if it is a polarization phenomenon. This question is a particularly legitimate one in view of the fact that many selenium cells show extreme polarization under the action of light and the electric current. I wish to state at the outset that none of the phenomena I have observed recently in light-positive and light-negative selenium arise from polarization by the current. My reasons for making such deductions with regard to the Giltay cell are as follows:

(a) First the selenium cell was balanced in a Wheatstone's bridge circuit after being intensely illuminated for several minutes. Then the battery circuit was broken. There was not the slightest deflection of the galvanometer by this procedure. This showed that no appreciable back E.M.F. was produced by the combined actions of the light and the electric current.

(b) Again the cell was connected in one arm of the bridge illuminated and balanced. The battery current was then quickly reversed by a reversing key. There was no apparent change of resistance. If there had been any polarization practically its whole effect would have had to disappear in less than a second. This might have been regarded as sufficient proof of the non-existence of polarization. (c) Next a test was made to see if the decrease of conductivity in the Giltay cell took place independent of the action of the current during the period of illumination. It was found, for example, that the conductivity at any time after the cell had been illuminated for 2 min. 10 sec. was that shown in curve 17 whether the current was flowing through the cell during the first two minutes or not.

At another time two series of observations were taken, one with the current acting all the time and the other with the current off during the first 60 seconds. The results are shown in the following table, where the conductivity in the dark is represented by unity, and where the observations were taken in the order enumerated by the sets.

Remembering that the current flowing through the selenium cell when the above observations were made was from 20 to 100 times larger than it was during the previous observations when the pronounced decrease of conductivity in the Giltay cell by light was noted, and allowing for the inconstancy of the light source, it may be concluded that the light action is independent of the current.

(d) Fearing that some might raise the question as to whether the 10 seconds allowed for the resistance determination might not be sufficient time for the current to produce the decrease under discussion, a further

TABLE VI.

Conductivity of Selenium Cell after Being Exposed to Light.

Time of Exposure.	Conductivity without Current Flowing in Cell.		Conductivity with Current Flowing in Cell. Sets III.
	Av. of Sets II. and IV.	Set IV.	
70 sec.	32.7		32.3
90 sec.	31.9		31.2
2 min.	30.7		30.3
		Av. of Sets III. and V.	
70 sec.	30.5		30.7
90 sec.	29.9		30.0
2 min.	29.2		29.1
		Av. of Sets I. and III.	
90 sec.	34.1		33.2
2 min.	32.9		32.2

test was made in which the mean time that the current flowed through the cell was 0.06 second. The pendulum before mentioned in this paper was used to first close the battery circuit for lighting the tungsten lamp when desired, then to close the battery circuit through the selenium cell and Wheatsone bridge circuit, and 0.01 sec. later to close the galvanometer circuit for a period of 0.1 sec. The resistance of the cell was 640,000 ohms and the fall of potential across it was about 0.1 volt. The following are the observations:

Time of Exposure, Seconds.	Deflection without Current Acting.	Deflection with Current Acting.
0.5	43.0	43.3
1.5	67.5	66.9
2.5	68.8	66.9
3.5	70.1	—
5.5	66.9	67.5
10.5	64.9	65.3 and 63.2

As in the previous observations the conductivity is a function of the deflection. The slight differences in the deflections with and without the current acting can be explained by assuming that the selenium had not recovered by the same amount for all the observations.

It may now be considered definitely settled that the decrease as well as the increase of conductivity in the Giltay selenium cell no. 2 represents a genuine change in the selenium or what is supposed to be selenium and not what is ordinarily termed polarization.

It has been shown by a great many investigators that the sensitiveness of selenium decreases with increase of temperature. However it has not been shown to my knowledge how the conductivity for different times of exposure varies with the temperature. As questions in the theory are involved in such information, I have obtained data at different tem-

peratures for time conductivity curves. Such curves are shown in Fig. 6. While the observations are not very accurate, and the range of temperature is not very great, yet it is safe to draw certain conclusions. The conductivity in the dark is more than four times larger at 46.5°C . than it is at 11°C ., and yet the maximum conductivity under the influence of intense illumination has nearly the same value. This is of course in agreement with the well established fact that the sensibility of certain selenium cells decreases greatly with rise in temperature. The maximum

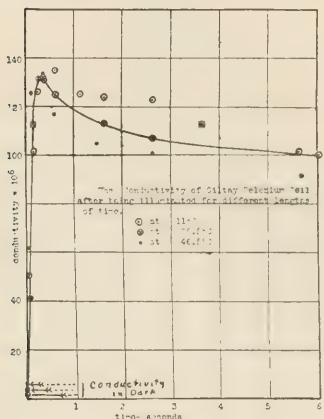


Fig. 6.

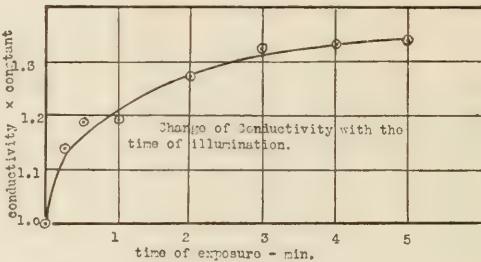


Fig. 7.

seems to be shifted toward the conductivity axis at higher temperatures. However there is reason for believing that the intensity of illumination was slightly less at the higher temperature than at 11°C .

Another class of light-positive selenium continues to increase in conductivity when it is illuminated. The selenium in the Bidwell and also the Ruhmer cells belong to this class. In Fig. 7 is shown how the conductivity varies with the time of exposure for a selenium cell of the Bidwell type. In this particular cell the resistance was only 8,000 ohms, and the sensibility was very low. The cell was not surrounded by a liquid while the readings were being taken; consequently a part of the observed change of conductivity may have been due to temperature. In

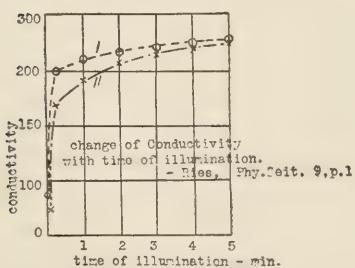


Fig. 8.

other cells of this class.¹ Curve I is for a cell that was slowly cooled in the making process, and curve II is for one that was quickly cooled in

¹ These are taken from a paper by Ries, *Phys. Zeit.*, 9, p. 9, 1908.

the making. He does not state the resistance of the cells or what was the intensity of illumination. For the cell referred to in Fig. 7, the intensity was that of a 16-cp. lamp at a distance 20 cm. When the intensity was greater than this the rise of the conductivity was more rapid at first and the final value was somewhat larger. In fact any light-positive selenium shows that the equilibrium value of the conductivity to increase with the intensity of illumination. Whether this equilibrium value varies in the same manner as does the conductivity for a very short period of illumination has not been investigated. Aside from the manner in which the "conductivity-time of exposure" curves differ in the two classes of selenium, there are two additional characteristic differences. The sensibility is much lower in the second class and the initial dark resistance is lower. At this time no special importance can be attached to the fact that the changes take place more slowly in the second class than in the first. The depth of the selenium and the intensity of illumination should be alike in order that such comparisons should be of particular value.

EXPERIMENTS WITH LIGHT-NEGATIVE SELENIUM.

Because of the difficulty of manufacture of selenium that decreases its conductivity upon exposure to light, I have not been able yet to determine the exact treatment of selenium that produces this so-called light-negative variety. In fact it took just as long and just as much patience to make the fifth sample as it did the first one. We shall therefore confine our attention to an analytical study of the behavior of these samples, particularly under the influence of light.

The general characteristics of this variety are not rigidly defined, except on a few points. The resistance is always small, and when the sample is first prepared it is very unstable. The smaller the resistance the greater is the sensibility, *i. e.*, the greater is the percentage change of resistance by light. Usually the amount of decrease of conductivity increases with increased illumination, but many times I have observed that a weak illumination such as the diffuse light of the room produces practically as great a change as does an intensity one hundred times as great. Generally the selenium recovers quickly when the light is removed, but after many exposures it may become fatigued and not recover for hours or at all. If the recovery is only partial then the sensibility is reduced. A few times and without any warning the selenium has for a single exposure become light-positive instead of light-negative. This was usually when the resistance was unsteady and when the selenium had been repeatedly illuminated. With one exception this reversal of effect has occurred only in newly prepared samples.

The following table will show the regularity of the increase of resistance of two samples which were about a year old. Unless otherwise specified the illumination was quite intense.

TABLE VII.

Table Showing by Successive Readings the Decrease of Conductivity in Two Samples of Light-Negative Selenium.

Sample No. 9.	Resistance in Ohms.	
Time of Observation.	In Dark.	In Light.
3:09	107	107.2 in diffuse light.
3:14	107.6	108.6 intense illumination.
3:17	107.6	108.6
3:25	107.6	108.4
3:32	107.6	108.7
3:54	107.6	108.7
4:06	107.65	108.7
4:21	107.6	

No. 2.

18.9	22.8 in diffuse light.
21.8	24.0 in diffuse light.
22.0	24.7 in diffuse light.
	25.2 20 cm. from 16-cp. lamp.
22.7	23.2 20 cm. from 16-cp. lamp.

When first made these samples showed the same amount of increase usually, but not only did the resistance in the dark shift very suddenly and irregularly, but the amount of the change in the light was very irregular and at times zero. The irregularities were made more pronounced by sudden changes of temperature or by very intense illumination. Table VIII. shows how the resistance gradually increased as the temperature was successively changed.

TABLE VIII.

Resistance in Dark, Ohms.	Temperature, Degrees Cent.
117	20
123	5
153.5	-10
148	0
157	20
191	3
189	4.5
196	-7
190	2
181	8
167	20
154	39
183	45

From this table it is observed that the general tendency is for the resistance to decrease by raising the temperature and for it to increase by lowering the temperature, but that the net result is an increase of resistance. Not only is the process not a reversible one, but often a change of temperature in either direction increases the resistance. The irregularities were exaggerated by extreme or rapid changes of temperature. All that has just been said however applies only to samples that have been newly made. The increase of resistance of sample no. 1 at the above temperatures was of the order of 1 ohm. By suddenly changing the temperature up and down as indicated in the above table and by tapping the selenium with a thermometer the resistance was further increased to 481 ohms at 24° C. It was then exposed to the light of a well lighted room for several months during the summer. All the time it was immersed in paraffin oil in a similar manner to that described previously as in use for the Giltay cell. At the end of the summer the selenium had increased in resistance to 6,200 ohms and it was not measurably sensitive to light. But this was not the most surprising thing. After being removed to the dark for a period of about a month its resistance fell back to 675 ohms, where it was somewhat unsteady and after the current was allowed to flow through it for an hour it fell still further to 67 ohms. It was then light-sensitive as before and has remained so for several months.

The way that the conductivity of these light-negative samples vary with the time of exposure is shown in Fig. 9. The lower curve is for

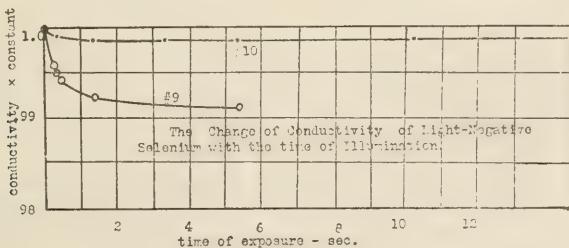


Fig. 9.

sample no. 9, which had a resistance of 107 ohms. The resistance of this sample was perhaps the most steady at all times of any that I have made. The upper curve applies to sample no. 10, which had a resistance of 312 ohms. It should be noted that almost all of the change takes place in less than a second. The intensity of the light was not much different from that used on the light-positive selenium which gave the results shown in curves 15, 16 and 17. The rate of decrease in the latter

case is about 200 times greater than it is in the Giltay cell. Further experiments should be carried on with this light-negative variety, in order to determine the conditions of stability and instability.

RIES'S "ABNORMAL SELENIUM CELLS."

Ries in his paper on the "Effect of Moisture on the Electrical Properties of Selenium"¹ discusses a most peculiar variety of selenium which he has produced. When illuminated these abnormal selenium cells first rise to a maximum very quickly and then fall off slowly to a minimum value, very much as noted for the Giltay selenium cell. Sometimes the conductivity would even decrease below the conductivity in the dark.

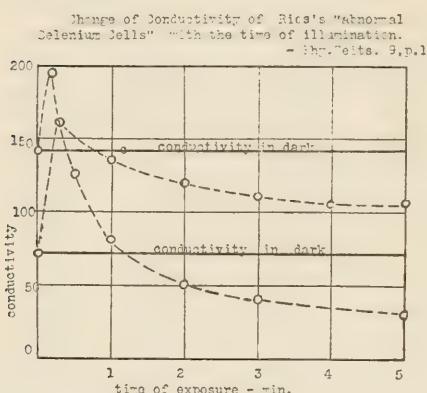


Fig. 10.

Two of his curves are shown in Fig. 10. The conductivity of these samples never increased much above that of the dark conductivity. The initial resistance and the intensity of illumination are not stated. He regards the decrease of resistance as a spurious effect which merely counteracts the positive light-action. His experiments indicate that moisture plays an important part in the formation and persistence of this variety.

I have not yet succeeded in reproducing his so-called "abnormal selenium cells," but this is no doubt because I have not duplicated the exact necessary conditions. I should prefer however to call this variety a third or modified type of the light-positive variety.

THE APPARENT FAILURE OF OHM'S LAW.

Ohm's law states that in an electrical conductor the current flowing is proportional to the difference of potential, assuming of course that all other conditions remain fixed. In all varieties of light-sensitive selenium this law apparently does not hold. As the voltage across the selenium is increased the current usually increases at a more rapid rate than it should. The amount of the change in the specific conductivity is sometimes very large. The curves in Fig. 11 show how the variation differs in the two classes of light-positive selenium. It is noted that in the Ruhmer cell the amount of variation is almost proportional

¹ Phys. Zeit., 9, p. 1.

to the voltage, while in the Giltay cell the variation decreases as the voltage is increased. The different high potentials were applied from 20 seconds to 1 minute before each observation was taken. It was suspected that the falling off of the effect in the Giltay cell was due to a decrease of the conductivity by the high potential much the same as is produced by light. This suspicion was strengthened by leaving the potential of 116 volts on the cell about a minute before taking the observation. It is seen that this point is below the curve. In other words, just as in the case of light the change of conductivity is a function of the time of application of the changing agent. The way that the decrease takes place is shown by the observations recorded in Fig. 12. This curve tells its own story when it is compared with the curves 16 and 17 in Fig. 5. There can be little doubt but that just as light produces a rapid change in the positive direction followed by a slow change in the negative direction, so are there corresponding changes produced by difference of electrical potential.

In order to be certain that

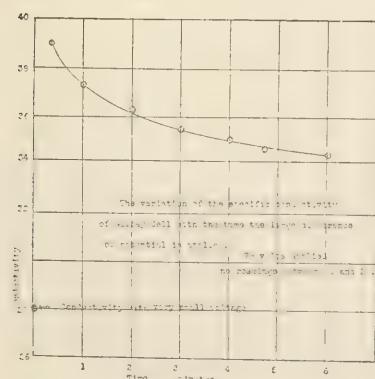


Fig. 12.

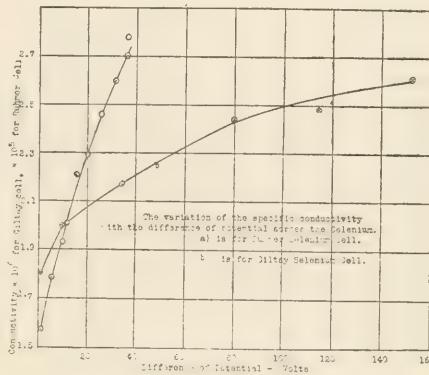


Fig. 11.

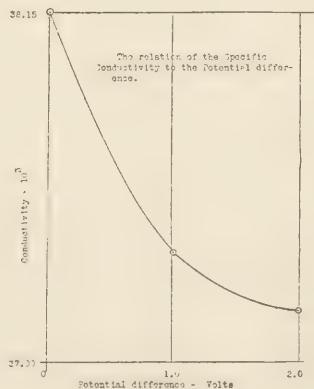


Fig. 13.

the variation first increased rapidly and then decreased slowly, the pendulum and ballistic galvanometer previously referred to were used. First the selenium cell was balanced in the Wheatstones bridge circuit where the fall of potential was two volts. Then the pendulum was

arranged to throw 120 volts instead of the 2 volts into the circuit for varying intervals of time. The galvanometer was in circuit during the last 0.1 sec. of the intervals. The deflection was a function of the change of resistance as usual. The relation of the change of resistance to the deflection may be estimated from the following:

$$\Delta x = 600,000 \text{ ohms}, \quad d = 3.5 \text{ mm.}$$

$$\Delta x = 650,000 \text{ ohms}, \quad d = 5.3 \text{ mm.}$$

$$\Delta x = 700,000 \text{ ohms}, \quad d = 7.5 \text{ mm.}$$

The following table, IX., shows that the maximum conductivity was reached in about 0.1 sec. The increase is rapid and large in amount and the decrease is small and slow in taking place.

TABLE IX.

Time of Application.	Deflection, mm.	Time of Application.	Deflection, mm.
.01 sec.	1.0	.10 sec.	27.3
.02	5.0	.10	26.0
.05	10.9	.20	24.2
.01	1.5	.50	22.5
.02	2.5	7.0	3.5
.02	5.0	10.0	2.7
.01	1.2	60.0	2.5
.05	22.5	60.0	2.0
.10	27.1		

The variation of the specific conductivity of light-negative selenium takes place within quite a different range of potentials than it does for the light-positive selenium. Between two and ten volts I could not detect any variation whatever with certainty. But between 0.001 and 2.0 volts the effect of the variation of the potential difference was unquestionable. The curve in Fig. 9 shows the effect of varying the voltage on light-negative no. 9. The readings were taken after the potential had been applied about a minute. There was evidence that the change was a function of the time also. However this change was so small that it could not be clearly distinguished from a possible temperature effect. The important conclusion is that the electrical difference of potential changes the specific conductivity and in the same direction as the change by light. I have one low resistance sample of selenium that continues to show the light-positive characteristics at times. Also its specific conductivity increases with increase of voltage. Further experiments must be carried on with this sample.

DISCUSSION OF RESULTS.

On the basis of our explanation we have deduced four particular characteristic equations, which show the relations existing between the time

of exposure and the conductivity. These relations are shown in the curves in Fig. 1. Experimental results bearing on these relations with all the known varieties of selenium are recorded. The thickness of the selenium varied between 0.1 mm. and 1 mm. While the thicknesses are unquestionably greater than is permitted by the theory because of the absorption of light by selenium, nevertheless it seems that the general form of the conductivity-time curves should not be materially different from what it would be if the layer were very thin. Experiments have not yet been completed for the determination of the depth of penetration of selenium by light, but the indication is that the light penetrates much deeper than is generally supposed, particularly in the light-positive varieties.

The results showed, that the Giltay cell gave curves very similar to 1 and 2, that the cells of the Bidwell type gave data for a curve like no. 3, that the light-negative selenium led to curves of the character of no. 5, and that Ries's "abnormal selenium cells" led to a curve like no. 4. I may state that I found data for curves of no other character to be obtained, either from the theory or from any variety of selenium that has come to my notice. I regard the striking similarity between these experimental and theoretical curves as important evidence in favor of the proposed theory. It seems a waste of time to try to fit the comparison curves more accurately until further information is obtained concerning the depth of penetration of selenium by light.

The curves in Fig. 4 show that with increased intensity of illumination the maximum conductivity occurs sooner, that the maximum is much greater, and that the equilibrium value of the conductivity is correspondingly greater. Any view of the theory requires that the rates of change shall be a function of the light intensity. The curves in Fig. 3 show how the maximum should be shifted if the reverse changes were small in comparison with the direct changes. The form of the curves agrees with the experimental curves, and the maximum occurs quicker with increased intensity. Also for faint illumination the change of conductivity is almost proportional to the time of exposure. This agrees with the relation of the conductivity to the time of exposure as determined by Stebbins. But there is disagreement on two fundamental points, viz., this assumption will not account for the different values of the maximum conductivity or for the different values of the equilibrium conductivity, for different values of illumination.

The curves in Fig. 2 show the manner in which the conductivity should vary with the time for a given intensity of illumination when there are different amounts of the three components. This is again on the assumption

tion that the reverse changes are small. All the forms of curves obtained with the different varieties of selenium are included in these curves. Also there is agreement in the fact that the highest sensibility selenium is that of the highest resistance and that of the negative variety is that of the lowest resistance. There are no disagreements between experiment and theory so far as these curves are concerned, unless we introduce a fact to be explained in a later paper, *i. e.*, that the conductivity of the *C* kind is small in comparison with that of the *B* kind.

Knowing the nature of the disagreement between experiment and theory when the reverse changes were supposed to be small, one can see at a glance that the particular disagreements should be removed if the reverse changes were not neglected. By taking into account the reverse changes as explained in the theory we not only removed the above discrepancies and obtained the curves showing all the characteristics required by the experimental results, but we also had a method of explaining the initial amounts of the three components and for explaining the recovery of selenium. Just what the agreement between the sign and the magnitude of the ratio of the sensibility to the initial conductivity may be cannot be defined further than is shown in Tables I. and II. There is no evidence of disagreement on this point. Satisfactory proof is lacking however in that Table I. does not consider all the possible relations. Theory and experiment agree on the following with regard to selenium of the variety found in the high sensibility of Giltay cells; the maximum conductivity occurs quicker with intense illumination than with faint; the maximum increases in value as the intensity increases; the equilibrium value of the conductivity increases with the intensity; for faint illumination the change of conductivity is almost proportional to the period of exposure.

There are some instances where no relation can be traced between theory and experiment. The ordinary effect of a rise of temperature is to produce a change in the conductivity in the same direction as that by light. But in the high sensibility cell the change by temperature is opposite to that by light. But since the temperature effect is in the same direction as in the pure metals and of about the same magnitude, we may say that the temperature effect is metallic in nature and refuse to explain it further. It is well known that the temperature effect in selenium cells is extremely large ordinarily. The curves in Fig. 6 illustrate this. It may be that the negative temperature effect exists in all selenium cells and that it is sometimes concealed by the much larger reaction temperature effect in the opposite direction. However the greatest difficulty in this line is with the light-negative variety of

selenium. The change by heat is opposite to that by light and also to that in metals by heat. I have no explanation to offer further than to say that the indication is that the light and temperature produce entirely different effects in this variety of selenium, and the same effect in light-positive selenium.¹

It is a noteworthy fact that in the Giltay cell a large potential difference produces a rapid increase in the conductivity which is followed by a decrease, almost identical to the changes produced by light except that the effects are not so large. As the two changes by light in the Giltay cells were found to be independent of the magnitude of the current one would naturally suppose that the large potential difference affects the conductivity as a result of electrical stresses in the selenium rather than as a result of the electric current. On this view the electrical forces would function in the dynamic equilibrium of the selenium.

Our experiments with selenium under pressure and those of Montén previously referred to show both a rapid and a slow change as noted for light and for high potentials. But the two changes here are difficult to measure accurately because of the simultaneous action of temperature. The equilibrium of selenium under pressure and temperature should be studied more carefully.

This dynamic equilibrium theory, if it satisfactorily explains all the observed phenomena, will still leave the whole subject in an unsatisfactory condition from one point of view. It will still remain to be explained why different varieties should have different rates of change. It may turn out that these different initial rates of change may arise from impurities which act as catalytic agents, or it may be if peculiar initial arrangements of the components are once established in the process of making, that there is an accompanying pressure or potential effect which maintains that peculiar arrangement. Some varieties of selenium do not have a fixed permanent stable equilibrium condition at once. They tend very slowly toward a new condition. In some cases moisture has been known to be the cause of such change but in others there is reasonable doubt. A semi-stable condition seems to exist in the light-negative selenium.

The way that light-sensitive selenium recovers when it is disturbed from its equilibrium condition by any agency is perhaps the strongest evidence in favor of the proposed dynamical theory. With the exception of some light-negative varieties of selenium, the selenium always recovers the conductivity that it possessed in the dark before illumination, and further

¹ On the similarity of the light and temperature effects, see paper by Miss L. S. MacDowell, *Phys. Rev.*, 31, p. 524, 1910.

the two changes that appear during the direct action also appear in the reverse process. The conductivity time curves may be called the reciprocals of the same curves for the action of light.

If the view is accepted that the conductivity changes only when the amount of the conducting variety is changed, then there is obviously no discrepancy in Ohm's law.

CONCLUSIONS.

1. That light produces two changes in the conductivity of opposite sign in all light-sensitive selenium.
2. That the amount of the change is a function of the time of illumination as well as the intensity and character of the illumination.
3. That the selenium in the Giltay cell shows the same two changes under the action of high potential differences that it shows under the action of light.
4. That the character of the conductivity curves for the four known varieties of light-sensitive selenium can be explained by assuming the existence of three components in dynamic equilibrium, under given illumination, temperature, pressure and electrical potential differences.
5. That the effect of any agency that affects the conductivity of selenium is of the nature that it alters the rates of interchange between the components.
6. That the experimental results can be explained to a first order approximation on the assumption that only the *B* kind is conducting, of the three components which are in equilibrium according to the reaction $A \rightleftharpoons B \rightleftharpoons C$.
7. That if we accept the view here proposed the failure of Ohm's law becomes only an apparent and not a real failure.

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A METHOD OF MEASURING THE FLUCTUATIONS IN A RAPIDLY VARYING RESISTANCE.

BY F. C. BROWN AND W. H. CLARK.

SOMETIMES it becomes necessary to measure a variable resistance which changes during short intervals of time. We have found that by placing the variable resistance in one arm of a Wheatstone's bridge circuit we can express its average value for any interval of time in terms of the throw of a ballistic galvanometer where the galvanometer is thrown into the circuit by means of a pendulum for the desired interval of time which must be small compared to the period of the galvanometer. How small this interval should be is also determined by the rapidity with which the resistance changes. If the time is made sufficiently short the average resistance practically becomes the actual resistance at the middle of the interval.

THEORY.

The theory of the method is quite elementary. Consider resistances without appreciable capacity or self-induction to be connected in a Wheatstone's bridge circuit as shown in Fig. 1. Suppose the battery resistance to be small compared to the other resistances. Let the balance be disturbed by changing the resistance in the variable arm by a small amount Δx . Then it can easily be shown that the current through the galvanometer is

$$i = \frac{E(bk_2 + k_1aR)(\Delta x)}{(k_1x + k_2)^2}, \quad (1)$$

where a, b, R and G are the resistances in the circuit,

$$k_1 = Gb + aG + bR + ab + aR,$$

$$k_2 = aRG + bRG + abR,$$

and

E is the electromotive force of the battery.

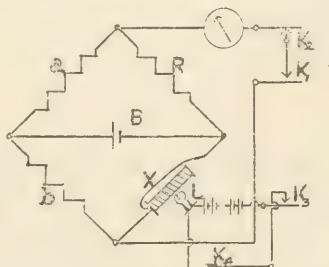


Fig. 1.

The quantity of electricity that is sent through the galvanometer may be expressed as

$$\Delta Q = i\Delta t,$$

or

$$Kd = i\Delta t, \quad (2)$$

where K is the constant of the ballistic galvanometer as obtained by discharging a known quantity of electricity through it and where Δt is the length of time that the current flows through the galvanometer. By combining equations (1) and (2) we obtain for the change of resistance,

$$\Delta x = \frac{Kd(k_1 x + k_2)^2}{\Delta t E(bk_2 + k_1 aR)}. \quad (3)$$

Now if Δx is small compared with x we may set

$$\frac{K(k_1 x + k_2)^2}{E(bk_2 + k_1 aR)} = C,$$

a new constant for a given set of resistances, and a given battery and galvanometer, and then

$$\Delta x = \frac{Cd}{\Delta t}. \quad (4)$$

The meaning of this equation (4) is that the change of resistance in the variable arm of the bridge is directly proportional to the deflection of the ballistic galvanometer and to the constant C , and inversely proportional to the interval Δt during which the galvanometer is in circuit. The change of resistance then can be calculated provided that it is small compared to the value of the resistance necessary to balance the bridge circuit. It will be noted that we have supposed that there is no appreciable damping of the galvanometer while it is in closed circuit during the interval Δt . The validity of this assumption will be considered later in the paper. Also the self-induction of the galvanometer is regarded as having no influence on the magnitude of the deflection.

Application to the Measurement of Small Changes of Resistance.—In order to test the linear relations between the deflection and the change of resistance and between the deflection and the interval Δt , known resistances were placed in the Wheatstone's bridge circuit shown in Fig. 1. The pendulum and keys were similar to those described in Carhart and Patterson's Electrical Measurements. A ballistic D'Arsonval galvanometer made by Leeds and Northrop was used. It had a period of 22.4 sec. A ballistic galvanometer with a period of 48.8 sec. was also used. To find the variation of the deflection with the change of resistance, the

keys k_1 and k_2 were placed a distance apart such that the interval during which the galvanometer was in circuit was $\Delta t = .05$ sec. Then the resistance in the variable arm was varied by different amounts previous to each reading. The readings were taken after the pendulum had operated the keys k_1 and k_2 . In this test the resistance remained constant throughout the interval. All the observations that were taken are recorded in Curve III. of Fig. 2. It will be noted that there is only a small percentage error in any single observation and further that for a change of resistance as

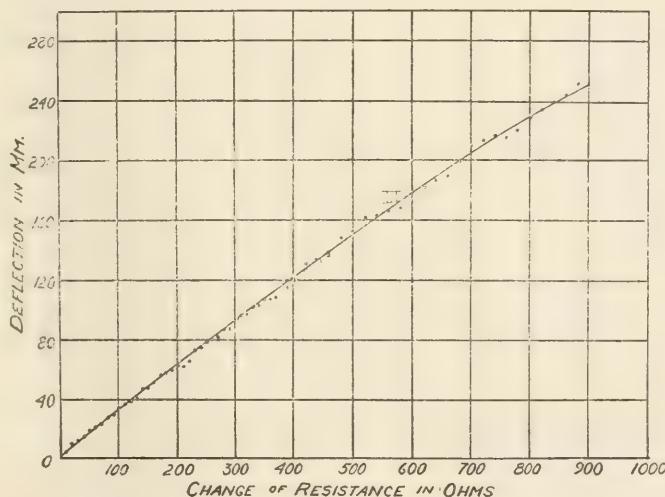


Fig. 2.

Relation between deflection and change of resistance; $a = 100$, $b = 100$, $R = 5000$, $x = 5000 - 4120$ ohms.

large as 800 ohms there is only a slight variation from the linear relation. For changes as large as $\Delta x = 200$ there is obviously complete agreement between the theory and experiment. It may be concluded here that the deflection is proportional to the change of resistance.

In order to test the relation between the deflection and the length of time that the galvanometer was in the circuit the variable resistance was changed a given amount, 15 ohms, from that required for equilibrium, and the distance between the keys k_1 and k_2 was varied. Observations were taken for both of the galvanometers referred to. These are shown in Curves I. and II., Fig. 3. Between .01 and about .12 sec. the linear relation required by equation (4) holds but from 0.12 sec. to 0.4 sec. there is a slight tendency for the deflection to grow less as the interval is increased. This slight downward bending of the time-deflection curves for larger intervals of time probably arises from the damping action of

the closed coil moving in the magnetic field, *i. e.*, the coil which required 5.5 sec. to move from zero to the end of the deflection had in the most unfavorable instance noted on the curve of Fig. 3 to move during the first 0.4 sec. with the coil closed through the Wheatstone's bridge circuit.

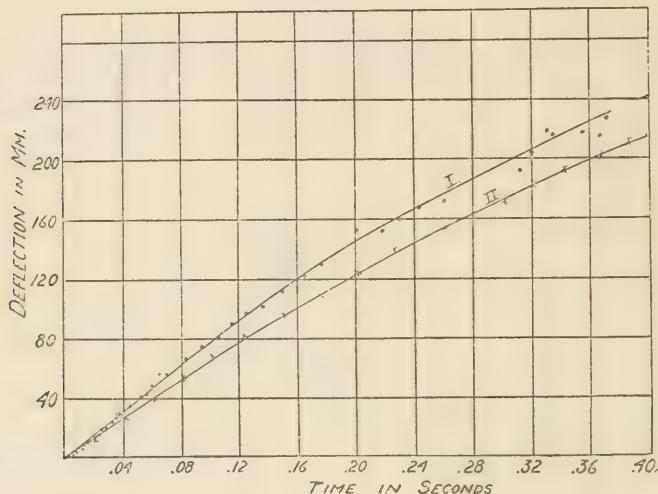


Fig. 3.

Relation between deflection and length of time the galvanometer is in the circuit. I. Galvanometer *E*. Period: 48.8 sec. II. Galvanometer *C*. Period: 22.4 sec.

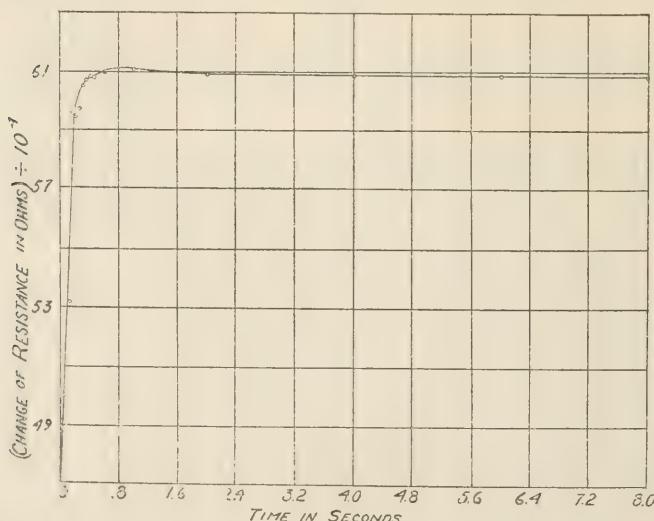


Fig. 4.

Change of resistance of a Giltay cell with time of illumination. Resistance in the dark 673,000 ohms.

The amount of motion during this time, about one thirteenth of the quarter period, probably damped the coil appreciably. It was quite definitely settled that the linear relation between d and Δt was obeyed for values of Δt as small as .0075 sec. but for values less than this there was considerable doubt. The apparatus used seemed to give deflections consistently too small when Δt was 0.005 sec. It may be stated then that the method suggested for determining changes of resistance is applicable through the use of equation (4) for quite a large range of values for Δx and Δt . The value of the constant C can be computed or determined by experiment. It is hardly necessary to state that the range of applicability will vary to some extent with the apparatus used. There will enter such factors as the sensibility of the galvanometer, the value of the resistances in the circuit, and self-induction.

However, for small variations in resistance it may in practice often be simpler not to compute the change of resistance from the deflection, but to merely substitute known changes in the variable resistance which will give the same deflection that was obtained with the unknown variable resistance, or to obtain enough deflections with known resistances so that the value of the unknown change can be interpolated.

The Measurement of Large Changes of Resistance.—In case the change of resistance, Δx is large compared with the initial resistance x , equation (4) can not be applied and equation (3) is not easily serviceable. The change of resistance is a function of the deflection regardless of how large it may be, but it is not easily computed. We have found the easiest way out of the difficulty to determine the deflections given by the unknown resistance at different intervals of time and then to substitute various known resistances which would give a range of deflection covering those obtained by the unknown. The deflections together with the values of the known resistances were plotted to give a calibration curve. Then the value of the unknown resistance or the change of resistance was read from the calibration curve.

A simple illustration will explain this application of the method. A Giltay selenium cell was connected at x in Fig. 1. The selenium cell was placed in a dark box in which was also a tungsten lamp. By closing both the keys k_3 and k_4 the storage battery circuit was closed through the tungsten lamp. This illuminated the selenium cell. The method of procedure in the experiment was first to balance the selenium cell in the bridge circuit, after it had recovered, and then to set up the keys k_1 , k_2 , and k_3 . Then the key k_4 was closed by hand. When the pendulum was afterward released it closed the key k_3 and illuminated the selenium cell. When the pendulum reached k_1 , the galvanometer was thrown in

circuit, and when k_2 was reached the galvanometer was thrown out of circuit. The time between k_1 and k_2 gave the interval of time Δt . The time taken for the pendulum to pass from k_3 to the midpoint between k_1 and k_2 was considered the corrected time of exposure of the cell to the light. After the pendulum had thrown the key k_2 , the key k_4 was opened by hand. If a period of illumination was desired that was greater than 0.60 sec., the absolute value of the period was not desired so accurately and therefore a crude auxiliary timing pendulum was used. The key k_3 was first thrown by hand and on the second the key k_4 was thrown, thus lighting the selenium and on any desired second the pendulum was released. This method kept the interval Δt constant and gave any period of illumination desired to a sufficient degree of accuracy. If the deflections by this method were too large they were reduced by changing the value of the battery electromotive force or by inserting resistances in series with the battery. Between each reading the selenium was allowed to recover.

The following table gives the observations that were made with the selenium cell.

TABLE.

Corrected Time of Exposure, Sec.	Deflections, mm.	Temperature.	Galvanometer Time Interval.
.05	7	24.8	0.05 sec.
.10	11	24.4	
.20	35	23.8	
.25	38	23.8	
.30	56	23.8	
.35	52	23.8	
.40	55	23.8	
.45	55	23.8	
.60	58	23.8	
1.00	61	23.8	
2.00	57	23.8	
4.00	56	23.8	
6.00	56	23.8	
8.00	55	23.8	

In the above observations the interval that the galvanometer was in the circuit was 0.05 sec. throughout. Using known resistance changes and the same interval 0.05 sec. data were obtained from which was plotted the calibration curve shown in Fig. 5. It will be observed from the calibration curve that for changes of resistance ranging in value from 500,000 to 564,000 ohms the deflection is almost a linear function of the change of resistance. For greater changes however the deflection changes very rapidly and becomes infinite when the change of resistance equals

the original resistance in that arm of the bridge. It is interesting to compare this curve with Curve III., Fig. 2. Both are deflection-resistance curves, but in Fig. 2 the change of resistance begins with zero while in Fig. 5 they begin with about 500,000 ohms. The resistances are of entirely different order of magnitude in the two instances.

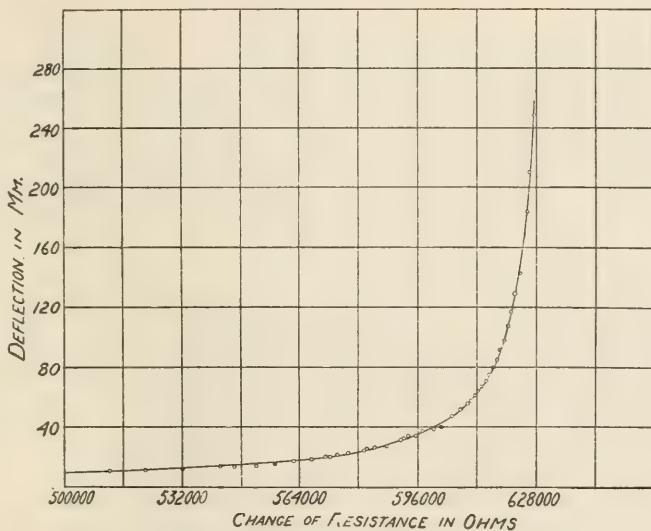
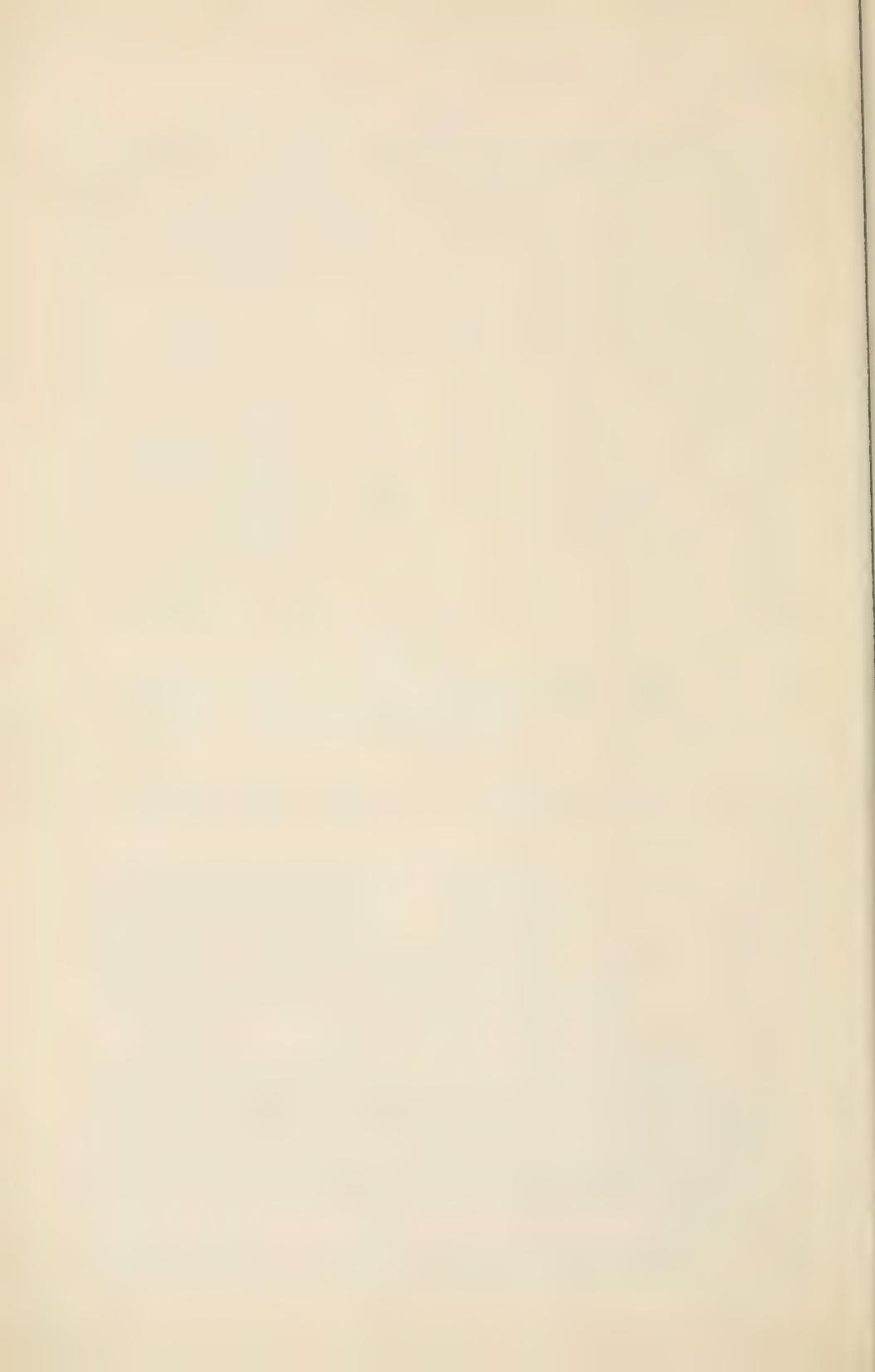


Fig. 5.

Calibration curve showing deflection for various known changes of resistance, when initial or equilibrium resistance is 632,000 ohms. Resistance in the other arms: $R = 6320$, $a = 1$, $b = 100$.

Using the values of the deflection obtained with the selenium cell shown in the accompanying table, we are able to determine the change of resistance from the calibration curve. The magnitude of the change for any time of exposure is shown in the curve of Fig. 4. The points on the curve each represent a single observation. The accuracy of a single observation is greater than we had expected. Almost without exception the points lie on the curve.

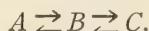
Other applications of this method may be found where it is necessary to vary the interval during which the galvanometer is in circuit and also the electromotive force of the battery. It may be stated in conclusion that the method is probably as accurate and as easy to manipulate as any method that has been devised for measuring such rapid fluctuations in resistance.



THE RECOVERY OF THE GILTAY SELENIUM CELL AND THE NATURE OF LIGHT-ACTION IN SELENIUM.

BY F. C. BROWN.

IN the July number of the PHYSICAL REVIEW¹ it was shown that the general behavior of the four known varieties of selenium under the action of light could be explained by assuming that the different varieties were merely differently proportioned mixtures of three components which were in equilibrium according to the reaction



In these considerations only the *B* component was a conductor of electricity. The amount of change of conductivity under the action of light at any instant was supposed to be proportional to the amounts of the changing components and to the rates of interchange according to the equations,

$$dB/dt = -(\alpha_2 + \beta_1)B + \alpha_1A + \beta_2C, \quad (1)$$

and

$$di/dt = kB/dt, \quad (2)$$

and the value of the conductivity at any time after illumination was calculated to be

$$i = L/N + c_1e^{m_1t} + c_2e^{m_2t}, \quad (3)$$

where *L*, *N*, *c*₁, *c*₂, *m*₁, and *m*₂ represent constants for a light of a given intensity when the temperature and other functioning conditions are unchanging. These constants are determined solely by the rates of interchange as shown. The method of procedure was to assign values for the rates of interchange and then compute the value of the conductivity for different times of exposure. By the use of rates properly chosen such constants were obtained for equation (3) that its graph could be made to conform in a general way with all of the curve forms obtained experimentally with the four known varieties of selenium. It was stated that the action of light was merely the alteration of the rates of interchange, particularly an increase in the values of the direct rates of change α_1 and β_1 , and further that the recovery from light-action was merely the process of restoration of the equilibrium amounts of the *A*, *B* and *C* kinds of selenium as the result of the smaller values of α_1 and β_1 prevailing in the dark.

¹ PHYS. REV., XXXIII., p. 1.

Therefore in the recovery of selenium equations (1), (2) and (3) must likewise be in agreement with the changes taking place, provided the proper values are assigned to the rates of interchange, and new limits are used in the integration such that

$$c_1 = \left[\frac{C_1}{\beta_1} + \left(\frac{L}{N} - B_1 \right) \frac{1}{\beta_2 + m_2} - \frac{L}{N\beta_2} \right] \left[\frac{(\beta_2 + m_2)(\beta_2 + m_1)}{m_2 - m_1} \right]$$

and

$$c_2 = \left[\frac{C_1}{\beta_1} + \left(\frac{L}{N} - B_1 \right) \frac{1}{\beta_2 + m_1} - \frac{L}{N\beta_2} \right] \left[\frac{(\beta_2 + m_2)(\beta_2 + m_1)}{m_1 - m_2} \right],$$

where B_1 and C_1 are the respective amounts of the B and C kinds at the instant the recovery begins. In the action of light the corresponding constants B_0 and C_0 represented the amounts of the same components when the selenium was in equilibrium in the dark.

Inasmuch as only the B component is conducting we may simplify our discussion by supposing that the units of conductivity are of such magnitude that B may be used interchangeably for either the amount of the component or the conductivity.

Whereas it was shown in the previous paper that the general behavior of all the known varieties of light-positive and light-negative selenium could be explained by the proposed theory, it will be shown in this paper for one of the light-positive varieties, viz., that found in the Giltay selenium cell, that the change of conductivity during both exposure and recovery can be explained quite accurately by the same theory. The Giltay cell furnishes evidence more convincing than some varieties of selenium in that some of its rates of interchange are very close to the critical values. A slight alteration of the rates by certain temperature changes will transform the experimental recovery curve from one type to a second distinct type of curve. And it will be shown that these two types of recovery curves are precisely what might be predicted from theory. The Giltay cell is particularly adapted for a critical test of the theory also because of its stability, sensibility and uniformity. If kept in the dark most of the time and subjected to no unusual treatment the selenium cells of the high resistance type made by Giltay maintain approximately their initial resistance and initial light-sensitiveness. It is thought that any work with the Giltay cell can be repeated with greater certainty than can work with any other light sensitive selenium on the market. As many can testify a special skill is required to produce selenium with specific rates of change. Mr. Giltay states that after making selenium cells for thirty years he still has surprises in his results. My high sensibility selenium cells are more sensitive than the Giltay

cells but they possess neither stability nor uniformity. The selenium cell used in these analytical investigations is the same one mentioned in the preceding paper.

EXPOSURE AND RECOVERY CURVES.

Selenium is difficult to investigate in that so many agencies alter its conductivity, and it is not always easy to eliminate all except the one under investigation. For example in studying light-action, there is a certain heating effect and also a change in the pressure on the selenium. The change in pressure may be due to change in volume of the selenium between the semi-fixed electrodes, as a result of the light-action and the temperature-action. The magnitude of these two effects is not easy to ascertain. In our theory we must consider these effects as due directly to light-action. Probably the effects just mentioned are not larger than the observational errors. In addition the radioactivity of the atmosphere, the moisture, and the barometric pressure alter the equilibrium condition and consequently the conductivity. In order to minimize the disturbing influences the selenium cell was placed in a kerosene oil, or paraffin oil, bath which was kept in motion continuously during observations by a stirring device. See Fig. 1. The kerosene oil bath was surrounded by a water bath which was also kept in motion by a stirring device, run by a motor. The temperature of the bath was regulated by an electric heating coil. The source of illumination was a 24 watt tantalum lamp with frosted globe. The lamp was inverted in a beaker which stood in the water bath. Unless otherwise mentioned the distance of the lamp was kept fixed at about 10 cm.

The intensity of the light was regulated by varying the resistance in series with the lamp. The large bath was kept light tight. It was considered that the advantages of this apparatus were that the selenium would remain at about constant temperature during observations and that all the surroundings except the lighted lamp would be at the same temperature as the selenium. There were fewer difficulties due to stray light than I have observed hitherto with other apparatus. The conductivity was read directly from a Siemens and Halske needle galvanometer in series with the selenium cell and a two volt storage battery.

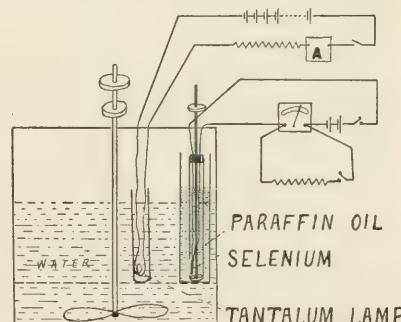


Fig. 1.

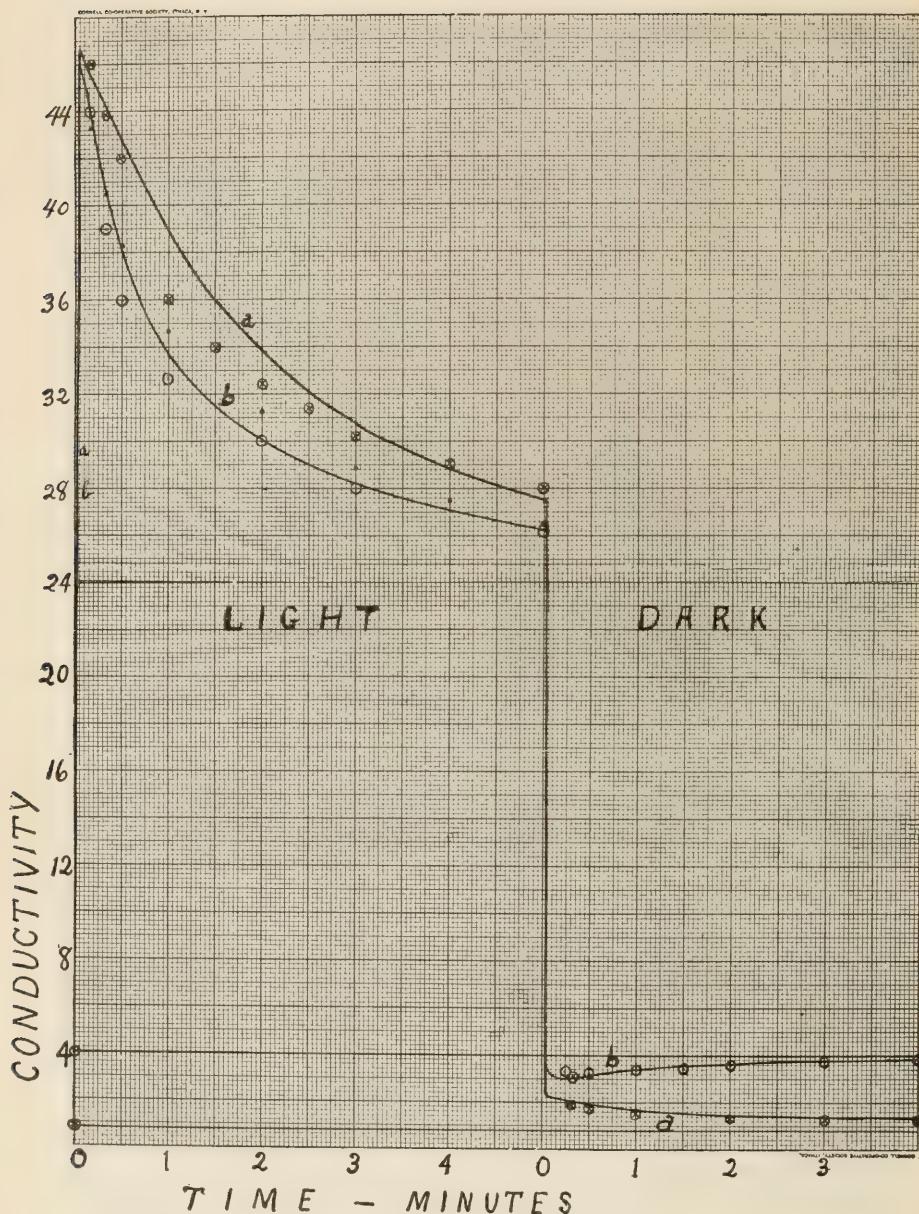


Fig. 2.

a represents the theoretical values of the conductivity during exposure and recovery at 18° C.; *b* is the theoretical curve for 52° C.; ○ represents the observed values of the conductivity at 18° C.; ○ represents the observed values at 52° C.; ● represents observed values at 28° C.

Observations were taken with the selenium at 18° C., 28° C., and 52° C., when the intensity of the illumination was that given by the tantalum lamp when the heating current was 0.43 ampere. The observations are shown in Fig. 2. It was impossible with the apparatus described to observe the more rapid changes which took place within a fraction of a second. The rapid changes due to the same illumination were measured by another method to be mentioned later in the paper. It may be noted that the conductivity under intense illumination is almost independent of the temperature. At the higher temperature the decrease of conductivity occurs somewhat more rapidly thus bringing the conductivity below that at lower temperatures. This may seem rather strange when it is noted that the conductivity at 52° C. begins at 4.0, which is five times that at 18° C., and two times that at 28° C. These facts are in substantial agreement with the results published in the previous paper, under less favorable circumstances. The maximum change of conductivity at the lowest temperature is about 110 times that in the dark, while the equilibrium conductivity is only 63 times that in the dark.

The recovery for the three temperatures is remarkably different. At 18° C. the first observation that could be made accurately was after 20 seconds, when the conductivity was more than twice that required for equilibrium in the dark. Although readings could not be taken accurately before 20 seconds, yet it was certain that at the end of the fifth second that the conductivity was not more than three times the dark value. After the first few seconds the remainder of the conductivity was regained very slowly. After four minutes it was fifty per cent. too high and after ten minutes the conductivity was yet 40 per cent. above the final value. In the recovery at 28° C. there was no observed difference in the rapid change but the slow change became much faster. After 15 seconds the conductivity was only 47 per cent. above the final value and after four minutes it was only eight per cent. The results that show that the rapid change taking place during recovery is not altered much by temperature will be given later.

At 52° C. the first observation that could be made showed that the conductivity was less than the final value as shown by curve *b*, Fig. 2. In fact it was about 25 per cent. too low for equilibrium. By further observations as shown in the same figure, the conductivity increased slowly during recovery until the equilibrium value was reached. After four minutes the value was 7 per cent. below equilibrium and after 8 minutes it was 5 per cent. Roughly the conductivity seems to increase during recovery only slightly faster than it decreased at the lower temperatures. But how much the difference depends upon the temperature,

At some temperature between 28° C. and 52° C. the selenium is in what might be called a critical condition, so far as the slow changes are concerned in the recovery. The slightest alteration in pressure, temperature, or other influencing agents might change the character of the recovery curve. In fact the selenium may be said to be in a critical condition at either 28° C. or 52° C. for a ten second exposure at 52° C. will give a recovery curve of like character to the one shown in Fig. 2 for 28° C.

These two types of recovery in the Giltay cell which are conditioned

TABLE I.

Giving the rates of change necessary to explain the observed values of the conductivity during exposure and recovery at different temperatures.

	18° C.	
	During Illumination.	During Recovery.
α_1	.054	0.00134
α_2	12.0	12.0
β_1	0.9	.018
β_2	0.004	.004
A	5,550	11,200
B	25	.8
C	5,625	3.6
Equation of conductivity	$B = 25 - 46.2e^{-12.5t} + 22e^{-0.0075t}$	$B = 0.8 + 24e^{-12t} + 1.25e^{-0.004t}$

	52° C.	
	During Illumination.	During Recovery.
α_1	0.3	0.025
α_2	12.0	12.0
β_1	0.3	.07
β_2	0.009	.009
A	1,040	1,892
B	26	4
C	860	30
Equation of conductivity	$B = 26 - 42e^{-126t} + 20e^{-0.016t}$	$B = 4 + 23.1e^{-12t} - 1.1e^{-0.01t}$

by temperature are very striking and they offer a rather severe test to our theory. However these diverse types can be explained theoretically by assuming that the action of the temperature change is merely an alteration of the rates of interchange. This was predicted in the previous paper referred to. In Table I. are given the rates of change during exposure and also during recovery which will explain the curves as obtained from observations when the selenium was at 18° C. and also at 52° C. The constants and the equations of conductivity result from

the rates of change, when calculated by the aid of the set of equations given in the previous paper and in this paper. Other rates might satisfy the experimental curves as well as the ones chosen. I can only state that the ones recorded are the best I could find. Everything depends on the rates. The quantity of only one kind of selenium must be taken arbitrarily to suit the units of conductivity chosen. The quantities of the other kinds both in the dark and in the light are calculated. As stipulated the sum of the three kinds can not change. In practice the value of the B kind for equilibrium in the dark was chosen to agree with the observed conductivity of the selenium in the dark. Then rates of change were found which would give the maximum and the final conductivity observed in the light. After obtaining agreement between theory and experiment for exposure it was fortunately very easy to obtain the same agreement for recovery. Afterthought showed that this is what should be expected. In fact if perfect agreement were obtained for exposure, then we should know almost without trial what rates should be proper to explain the recovery observations. The recovery and exposure, as a study of the theory will show, are closely correlated. The graphs of the equations in Table I. are represented in Fig. 2 by the continuous curves. It will be observed that the conductivity curve is always continuous.

It is surprising indeed that the agreement between theory and experiment is so close as shown in Fig. 2. This particular case was chosen as the most difficult one to explain that could be obtained with any variety of selenium under any conditions. The extreme range of the conductivity and the peculiarity of the curves would have made a much worse agreement satisfactory. It is not certain that the rates given in Table I. are more than approximately correct. However later thought shows that they are of the right order of magnitude and probably vary only in the second place from the true values. But what is most important at this stage of our investigation is to find out what light and temperature do to the rates of change, and to inquire if the things that happen are consistent and reasonable. It may merely be noted here from Table I. that light increases the direct changes α_1 and β_1 and that a temperature rise increases all the changes except possibly the reverse rate of change α_2 . The relative action of light and temperature as shown is of much interest but we shall reserve discussion on this point until later in the paper when we have considered more comprehensive data.

CHANGE OF CONDUCTIVITY DURING EXPOSURE AND RECOVERY FOR FAINT ILLUMINATION.

In the discussion just preceding the intensity of the light may be considered as relatively great although it was probably not larger than 32 cp. at 10 cm. In general it is important to check theory and experiment under conditions that allow the greatest change, but in this instance it is also quite necessary to find agreement where the illumination is not intense and where there is consequently only a small change in the conductivity.

In order to predict what difference may be expected between faint illumination and intense illumination, we must first define what we mean by faint and intense. We will consider the wave front of light as speckled at any instant with light and dark spots of small dimensions, and that the light spots travel about over any uniformly illuminated surface in such a manner that after a few seconds any one finite area shall have been hit by the same number of light spots as any other equal area on the surface. This is the well known spotted wave front theory¹ proposed by Sir J. J. Thomson,² and others. The intensity will be defined as the average number of light spots per unit area at any instant. Thus the essential difference between the action of an intense light and a faint light on selenium lies in the difference in the number of particles acted on at any instant, or we may say in the difference of rate of action. If light acts on selenium until saturation is produced there will be just as many particles struck and changed by light per second as recover per second. Light of small intensity acts on only a small number of particles per second, while an intense light acts on a relatively large number. Every particle that is struck with faint light will change just as much as it would if struck by an intense light, but before it is struck a second time it will be almost recovered. The interval between successive impingements of a faint light on the same small region is relatively large. And so on the average for all the particles, they will be almost recovered all the time. The result is that the rates of recovery for faint illumination will be smaller than for intense illumination. More will be said on this point in the discussion of the experimental results obtained.

The observations with faint illumination were taken under about the same circumstances as those previously described with intense illumination. The source of light was the same tantalum lamp when it was carrying 0.11 ampere as heating current. As before the entire surface

¹ See paper by Sir J. J. Thomson.

² Proc. Camb. Phil. Soc., XIV, p. 41, 1908.

of the selenium was illuminated. The intensity was so regulated that the conductivity would be about doubled by the light. The temperature was about 26° C. The observed conductivity at all times during both exposure and recovery is shown in Fig. 3. In Table II. are given the

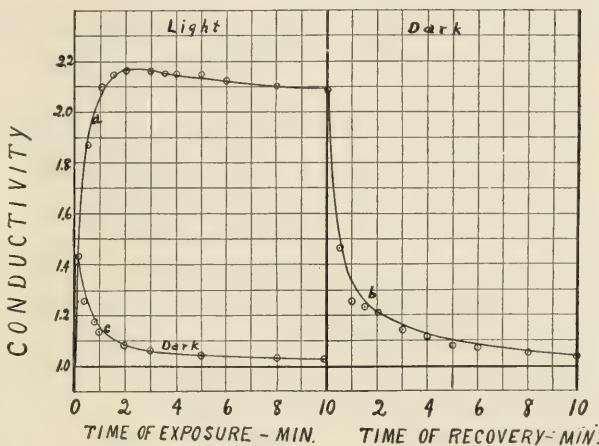


Fig. 3.

Exposure and recovery curves with faint illumination. *a* is the theoretical curve for exposure; *b* and *c* are theoretical curves for recovery; \circ represents the observed values.

rates of change during exposure and recovery which would cause the conductivity to vary along the continuous lines *a*, *b*, and *c*. The agreement is found to be within the limits of experimental error and is as good as could be hoped for. It is particularly noteworthy that the same rates of change explain the recovery at the end of a ten-second exposure that explain the recovery at the end of a ten-minute exposure.

TABLE II.

Giving the constants and resulting equations necessary to explain the exposure and recovery curves when the selenium is exposed to faint illumination at 26° C.

During Illumination.				During Recovery.			
α_1	0.004						0.00132
α_2	0.02						0.02
β_1	0.01						0.0053
β_2	0.003						0.003
<i>A</i>	15.6	Before	10.2	Values at end	13.9	Values at end	
<i>B</i>	1.0	illumina-	2.86	of ten min.	1.42	of ten sec.	
<i>C</i>	1.8	nation.	5.4	exposure.	3.11	exposure.	

$$B = 2.06 - 1.17e^{-0.03t} + 0.17e^{-0.03t} \quad B = 1 + 0.83e^{-0.03t} + 0.23e^{-0.026t} \text{ for 10 min. exposure.}$$

$$B = 1 + 0.35e^{-0.03t} + 0.08e^{-0.026t} \text{ for 10 seconds exposure.}$$

The initial values of the three kinds of selenium for recovery after a ten-second exposure are calculated by the aid of the equations given in

the previous paper. It must be remembered that the initial conditions during recovery are determined by the rates during illumination and conversely that the initial conditions during exposure are dependent on the rates during recovery, as well as the time of recovery. No experiments were made to check theory and experiment where the selenium had only partially recovered but I have no doubt whatever but that the agreement would be as satisfactory as the other results.

THE RECOVERY WITH DIFFERENT DURATIONS OF EXPOSURE.

We have shown for intense light at certain temperatures and for a given period of illumination that the reverse change between the A and B components is large compared with the reverse change between B and C . This suggests at once that the recovery of B into A may be determined directly by measuring the resistance changes over such short intervals of time that no appreciable amount of the C kind is changed into B . In order to predict what change in B may be expected, we will substitute the rate values during recovery and also the amounts of the components, as found in Table I, into equation (1). This gives

$$dB/dt = - (12 + .14) \times 25 + 0.0025 \times 1923 + 0.004 \times 100.$$

We observe from this that so long as B is large compared with unity, that the change in B should be almost proportional to the amount of B present at any instant, regardless of the amount of A and C . This conclusion may obviously be stated in the following form: the change of conductivity for short intervals during recovery divided by the con-

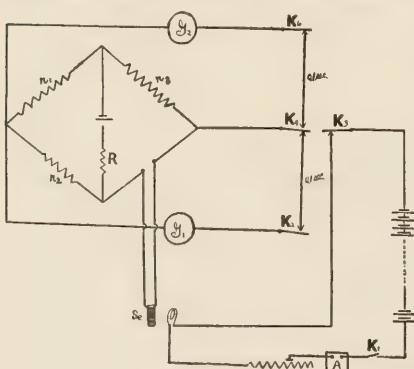


Fig. 4.

ductivity should be a constant for large values of B and constant illumination.

To test the above relation the selenium was exposed to the tantalum lamp, carrying 0.35 ampere, for various lengths of time, and the mean conductivities were measured during the last 0.1 second of exposure and during the first 0.1 second of recovery. This was accomplished by a modification of the method of measuring fluctuating resistances

described by Brown and Clark.¹ Two galvanometers instead of one were used, as shown in Fig. 4. The pendulum that operated the galvanometer

¹Phys. Rev., XXXIII., p. 53, 1911.

keys also opened the lighting circuit. The first galvanometer was thrown into circuit only during the last 0.1 second of exposure and the second galvanometer was likewise in circuit only during the first 0.1 second of recovery, after the selenium was darkened. By the usual calibration the deflections were translated into the equivalent mean conductivity during the interval in question. The period of one of the galvanometers was increased by adding a lead rider to the moving coil. This enabled one observer to read both galvanometers. The selenium cell was left in the bath arrangement previously described. The temperature was 22° C. An hour or more elapsed between observations to allow the selenium to recover. The results of the observations are shown on the curves in Fig. 5. The points on the upper curve resulted from observations made on the first galvanometer, and the points on the lower curve were calculated from the deflections of the second galvanometer. The difference between any pair of observations recorded on the two curves divided by the higher value gives the mean fractional part of the conductivity recovered between zero and 0.1 second. This fractional part or per centage recovery is recorded in Fig. 5 for each pair of observations. I was surprised myself at the constancy of these percentages. The conductivity varies by at least forty per cent. and yet it is doubtful if the percentage recovered varies as much as one per cent. when the time of exposure varies from 0.4 second to 240 seconds. As the first value is low however there may be some doubt as to the constant percentage recovery for exposures of only a fraction of a second.

The mean percentage recovery recorded during the first 0.1 second was about 30. If we assume that this value was reached in 0.05 second, then we obtain for the rate of change of B into A , $\alpha_2 = 12$. This is in agreement with the curves in Fig. 2, for which no observations were

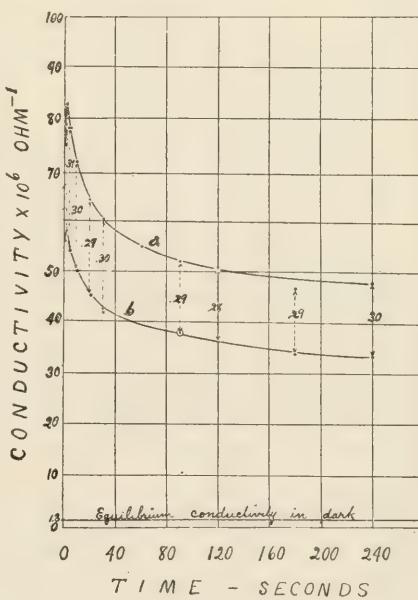


Fig. 5.

The upper curve (a) shows the conductivity for any period of illumination from 0.4 second to 240 seconds. The lower curve (b) shows the conductivity of the selenium after recovering 0.05 second following any period of illumination. Conductivity in dark 1.3.

taken directly for periods less than ten seconds. In fact the result here recorded was used as an aid to obtain the correct rates of change to explain the observations in Fig. 2.

By the same method recorded in this section the recovery during 0.1 second was measured at 40° C., and it was found that the fractional part recovered was 34 per cent. This indicates quite directly what was shown in Table I., that the value of the reverse rate of change α_2 is altered little if any by temperature changes.

In Fig. 6 is shown the percentage recovery for exposures between zero and six seconds. In taking these recorded observations the selenium was not placed in a bath, but nevertheless they are substantially in agreement with the other results. The

intensity of the light was less than in the other instance, and the pendulum keys were so arranged as to give the recovery after 0.1 second and not the mean recovery between 0 and 0.1 second.

THE VARIATION OF THE RATE OF RECOVERY WITH THE INTENSITY OF EXPOSURE.

A comparison of the data in Tables I. and II. indicates that the rapid rate of change α_2 varies greatly with the intensity of illumination. After the thorough investigation mentioned in the last sections was made, which showed that the value of α_2 did not vary with the time of exposure within very wide limits, it was thought advisable to investigate the effect of varying intensity by the same method. The same apparatus referred to in Fig. 4 was used. However, when the change of resistance was small the first galvanometer was used to measure the equilibrium resistance in the dark and the resistance at the end of a three minute exposure by the ordinary Wheatstone's bridge method. The second galvanometer measured by its throw the mean change of resistance during the first 0.1 second after the light was extinguished. The period of illumination was kept constant and the intensity was varied by changing the heating current in the lamp. As I have not yet considered quantitatively the effect of varying the intensity of the light, I have not yet taken the trouble

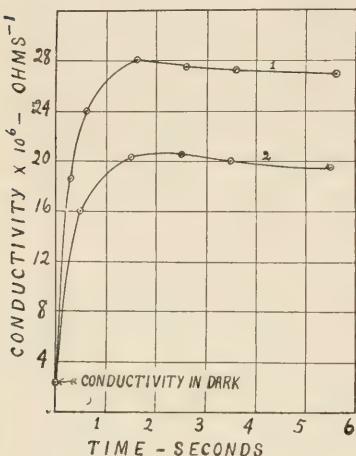


Fig. 6.

(1) Conductivity before recovery. (2) Conductivity after recovering during 0.1 sec.

to interpret the intensity in the usual units. A sufficiently accurate notion of the intensity for our present discussion may be estimated from the value of the heating current and also from the change of resistance of the selenium. The results of the investigation are given in Table III.

TABLE III.

Time.	Current in Lamp Amperes.	Temper-ature.	Poten-tial Across Cell, Volts.	Time of Ex-posure.	Resist-ance in Dark.	$\frac{1}{B}$ Resist-ance in Light.	Deflec-tion.	$\Delta B \times 10^3$ Ohms $^{-1}$.	$\frac{\Delta B}{B}$ Mean Percent-age.
10:55 A. M.	0.15	27.8°C.	2	3 min.	680,000	159,000	6.1		
11:45					680,000	158,000	4.0		
1:00 P. M.					700,000	156,000	4.0		
					Mean		3.7	0.016	2.5
9:02 A. M.	0.20	28.0	2	3	740,000	74,000	14.5	0.11	
9:53					710,000	74,000	14.6	0.11	
1:15 P. M.	0.45	27.5	2	3	700,000	16,300	74.		
3:50					677,000	16,900	73.		8.2
6:30	0.33	27.7	2	3	703,000	28,200	64.	1.05	29.6
7:25	0.355		2	3	710,000	23,000	73.	1.44	33.1
9:40	0.40	27.9	2	3	680,000	19,700	76.8	2.04	40.2
10:55	0.3	27.5	2	3	705,000	34,000	67.0	0.72	24.0
12:04	0.25	27.8	2	3	683,000	49,400	39.3	0.31	15.3
2:38	0.22	28.1	2	3	660,000	62,000	28.0		
5.30							24.0	0.18	11.2

The value of $\Delta B/B$ varies from 2.5 per cent. for the faintest light measured to 46.5 per cent. for the most intense light. It may be stated without qualification that $\Delta B/B$ increases with increased intensity. The rate of change as calculated from the value 0.025 is only slightly larger than the value given for α_2 in Table II., where the conductivity was somewhat less. This is as it should be.

In obtaining the data in Table III. the character of the light varied as well as the intensity did, and the same may be said for the comparative observations in Figs. 2 and 3. Just what difference arises from the altered character of the light can not be predicted with any certainty, but the assumption that the characteristic difference in the results noted is due to a variation in the light intensity can not be far wrong. It was shown in the previous paper¹ in a general way that when the character of the light source was practically constant, and when the intensity of illumination was varied by varying the distance of the source that the

time required for the maximum conductivity to be reached during exposure increased with decreasing intensity.

THE EFFECT OF SHORT EXPOSURES.

The effect of short exposures to either intense or faint illumination is to produce the changes that take place rapidly but it does not follow that the recovery should be correspondingly less for short exposures, than it would be for long exposures. If there is a large increase in the conductivity as a result of a short exposure, during exposure the conductivity component changes both into the *A* kind and the *C* kind, and it will be noted from Table I. that the rate of transformation into *C* is relatively quite large. It follows that before equilibrium is reached all of the *C* kind must be retransformed back into the *B* and *C* kinds, which is of course a slow process. Again this notion is confirmed by the equations of the conductivity, in which the exponential coefficients are determined solely by the rates of change, while the constants c_1 and c_2 are determined both by the rates of change and the time factor.

That the preceding explanation for the recovery from short exposures is probably the correct one, may be inferred further from the observations shown in the curves in Fig. 7. The selenium at 20° C. was exposed to a

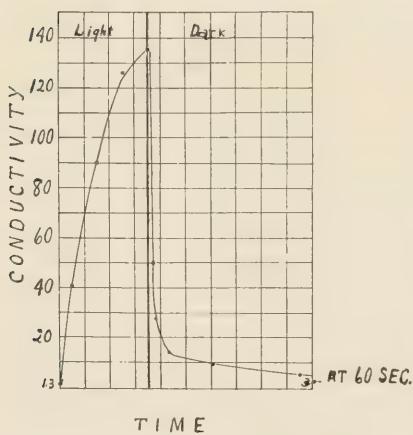


Fig. 7.

Each division represents 0.1 second.

Probably the most surprising fact is that both theory and observation show that it requires longer for selenium to recover its conductivity after exposure to a faint light than it requires to recover from a long exposure to a very intense light.

very intense light, roughly a 32 cp. tungsten lamp at 7 cm. distance for a period of 0.35 second. This period was just about sufficient to allow the selenium to reach its maximum conductivity, *i. e.*, the condition when there was the maximum amount of *B* present. This was one hundred times the amount of *B* present in the dark equilibrium condition. After 0.85 second only about 85 per cent. of the conductivity change is seen to be recovered. And even after 60 seconds it was still twice what it should be for equilibrium in the dark at that temperature. Prob-

For high temperatures also the recovery from very short exposures is similar to that shown in the last figure, but more rapid. But for longer exposures the recovery is like that shown in Fig. 2. This is in general agreement with the theory. For short exposures there is only a small amount of the *B* kind transformed into the *C* kind and consequently the conductivity should be continually diminishing. If the exposure is continued then there is such a large amount of the *C* kind produced that the *B* kind first diminishes rapidly below the dark value in order to approach equilibrium between *A* and *B*, and then increases slowly until the equilibrium value is reached. Here caution is urged against assuming that selenium is in equilibrium merely because the equilibrium value of the conductivity is reached. In case the selenium is in apparent equilibrium, but in reality not, the sensitiveness to light is diminished just as might be expected if the amount of the *A* kind present were too small. For a long time this diminished sensitiveness to light was very puzzling to me.

THE RECOVERY FROM THE EFFECTS OF HIGH POTENTIAL DIFFERENCES.

It was stated in two earlier papers¹ that the change of conductivity of selenium by high potential differences was of the same nature as the change by light. This conclusion was based largely upon the fact that the light sensitiveness of the selenium diminished as the potential difference between the electrodes was increased, and also upon the fact that

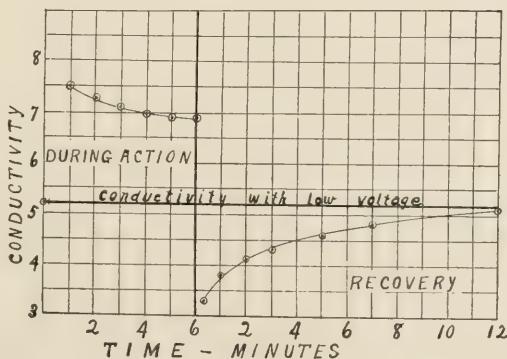


Fig. 8.

Curves showing the conductivity of the selenium during the action of 152 volts potential difference and during the recovery.

both agencies acted in such a manner as to first increase the conductivity and then to decrease it. Further consideration shows that both effects

¹ PHYS. REV., XXVI., p. 273, 1908, and XXXIII., p. 1, 1911.

are similar, in that they alter the rates of interchange and consequently increase the amounts of the *B* and *C* kinds. But the rates are altered in quite different proportions by the two effects. Light acts chiefly on the rates between the *A* and *B* components while the high potential acts about as much on the *B* and *C* components as on the others. Observations that were taken during action and recovery with 150 volts are shown in Fig. 8. I have not yet succeeded in obtaining any accurate notion of the rapidity of the more rapid change. Before an accurate comparison of the rates can be made it will be necessary to measure the rapid changes.

THE INTERPRETATION OF THE RESULTS.

We have shown that the proposed kinetic reaction theory agrees in a general way with all the varieties of selenium known and further that when tested in particular with one of the most complicated the agreement is all that could be hoped for. It has not been necessary to impose any conditions that are unreasonable or that complicate the simplicity of the argument. But having established the theory thus far to a fair degree of accuracy, it is of interest to inquire what may be its further physical significance.

It has not been necessary to assume that more than one of the three components are conducting and further it has not been necessary to assume that light acts in the least degree on the reverse rates of change. In both these respects the theory is less complex than when it was first proposed. These facts have been tested for intense light at two widely varying temperatures. In fact the temperature difference was so great that the initial conductivity in the dark differed by a factor of five. The light was so intense that the conductivity in one instance had a maximum value 110 times that in the dark. That only the direct changes are necessarily altered by light was also shown for light so faint that the maximum conductivity was only twice what it was in the dark. There can be little doubt but that for light effects one hundred times smaller than this, we would also find that only the direct rates would necessarily be altered. The generality of this conclusion is not only interesting but also a big advance in our theory. It should simplify the physical interpretation and at the same time reduce the difficulties in the mathematics.

TABLE IV.

Ratio of Rates in Light to Dark.	Intense Light at 18° C.	Intense Light at 52° C.	Faint Light at 22° C.
α'_1/α_1	40	12	3
β'_1/β_1	50	4.3	1.9
α'_2/α_2	1	1	1
β'_2/β_2	1	1	1

That light may act on the rates in about the same way for intense light as for faint light is shown in Table IV., which is compiled from the data in Tables I. and II. To distinguish between rates, those prevailing during light action are primed.

Attention should be called to the fact that at different temperatures and with different intensities of light, we do not suppose the existence of the same total amount for the three components. The meaning of this is not certain. The total amount might possibly vary with temperature but this could hardly be the case with varying intensity. Possibly the amounts considered are partially fictitious, and that as previously alluded to, an intense light acts on a large proportion of the components present, while a faint light acts on only a relatively small proportion at any instant. It may be suggested here that the different initial rates of change that analysis shows to exist in the four known varieties of selenium, may in some cases arise from a difference in the attractive power of the components for certain molecular aggregates either in the solid or gaseous state. Obviously the impurities might modify the rates unequally for the different components. I hope to develop this idea further later in explaining certain unstable samples of selenium.

In the original paper it was assumed that the light was of uniform intensity throughout the selenium at any instant. Now in order that our analysis shall apply to the facts, we must understand that the light shall have what might be called only an average uniformity.

The rates of change that are given in this paper assume that light acts throughout the conducting layer of selenium. The fact that the rates are so consistent with each other and that they so satisfactorily explain the observations would lead one to suspect that the above assumption is not far wrong.

THE EFFECT OF OTHER AGENCIES.

A study of the tables shows that our previous predictions concerning the similarity of the action of light and temperature still seem to be consistent. So far as light action is concerned it is necessary to assume that temperature alters the direct rates α_1 and β_1 to a very large degree. However in addition to this, temperature produces a slight change in the reverse rate β_2 and possibly also a minor change in conductivity of which no account is taken in our theory. The fact that temperature alters three of the rates will probably make it easy to explain the numerous temperature coefficients that are possessed by the different varieties of selenium. Temperature no doubt acts throughout the conducting layer of selenium. This being assumed we have at once an easy method of estimating the relative depth of penetration of selenium by light.

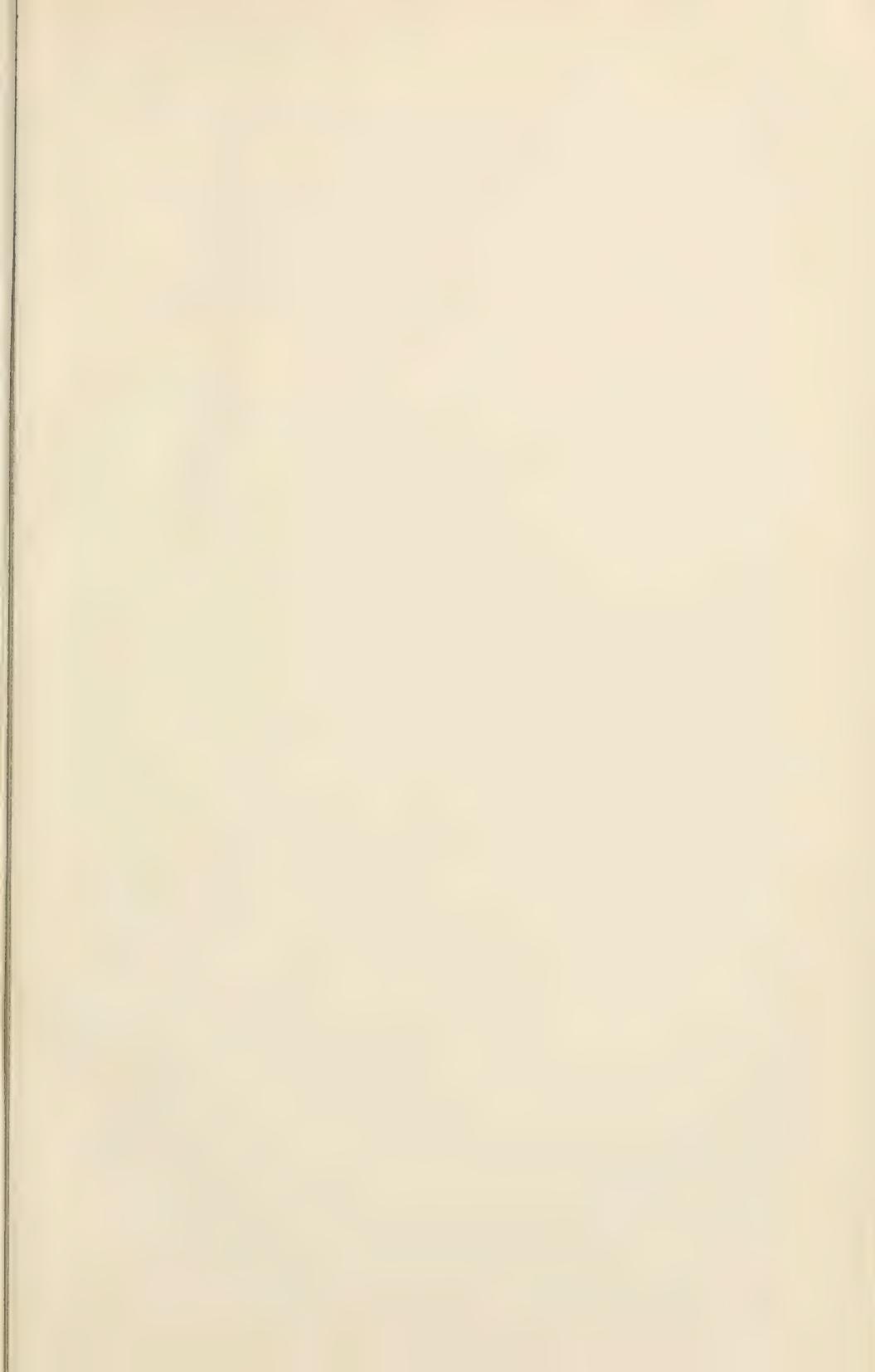
The behavior of selenium under the action of pressure, radium, X-rays and other agencies should aid us in the interpretation of our results. The fact that selenium recovers very slowly from radium action as pointed out by Brown and Stebbins or X-ray action as pointed out by Miss MacDowell¹ can be explained satisfactorily if we assume that these agencies have compared to intense light a low frequency for any point region. It seems that this is the most reasonable assumption to make. Further if selenium is suddenly relieved from a very high pressure it should recover much more rapidly for the rapid part of the change, than it does from illumination of ordinary intensity. What observations we have made on this point indicates this high rapidity of recovery for either small or large pressures. However, we were not prepared in 1907 to measure this rapid rate. Further investigations on the rate of action by other agencies will no doubt show that the proper assignment of rates of interchange will explain the larger part of the changes taking place, but the values that are obtained may modify our interpretation materially.

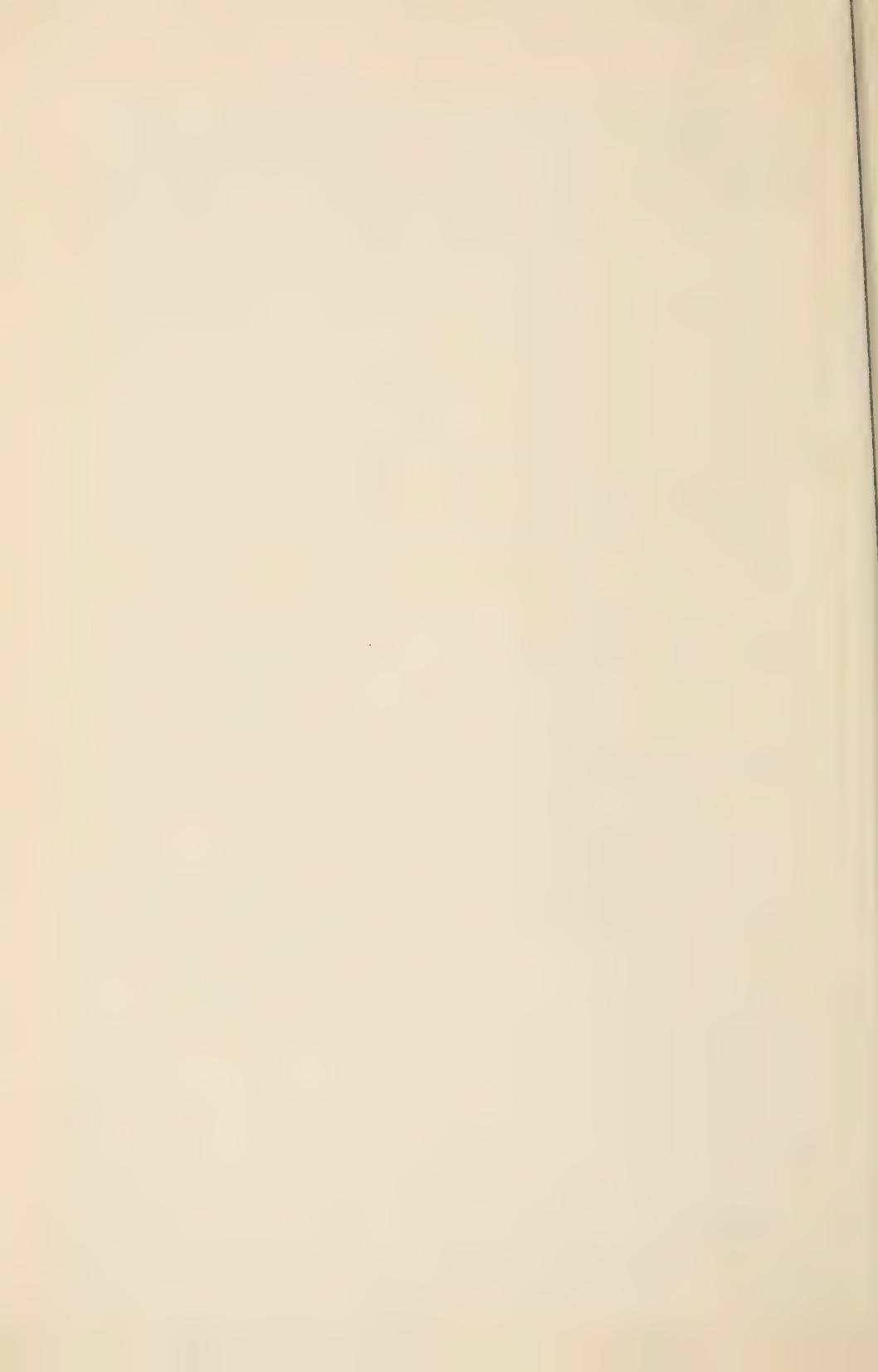
SUMMARY OF CONCLUSIONS.

1. Without making any allowance for the fact that the light does not probably penetrate throughout the conducting layer of selenium, the theory agrees fairly satisfactorily with the observations over a wide range of temperature and light conditions.
2. Only one of the three components is conducting.
3. Very direct experiments show that for at least one case the change in the conductivity is proportional to the amount of the changing component.
4. Temperature action in the Giltay selenium cell is essentially the same as light action but not identical to it.
5. More careful and more extensive work should be carried out to determine the full significance of all the rates of interchange.

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¹ PHYS. REV., XXX., p. 474; also paper by M. Perreux, Comptes Rendus, Vol. 129, p. 956.





CERTAIN CHARACTERISTICS OF LIGHT-NEGATIVE SELENIUM.

BY LILAH B. CRUM.

THE change of resistance in light-positive selenium under the action of light occurs in one of two distinct types. Which is followed seems to depend in some manner upon the magnitude of the change, or, in other words, upon the sensitiveness of the unit.¹ When units of low sensitiveness, which are also of low resistance, are exposed to light, their conductivity increases rapidly at first, and then more and more slowly, while the conductivity of the high sensibility, or high resistance units rises quickly to a maximum value, and then falls off more and more slowly. But whichever type of action is followed, the selenium always shows an increase of conductivity immediately after exposure to light.

Ries² records the action of a selenium unit, where the fifth day after its manufacture the falling off in conductivity after the maximum had been reached was great enough to bring the conductivity in the light to a value below that which it had shown in the dark. But he concluded that this strange effect was due to the presence of moisture.

The first selenium units which decreased their conductivity immediately upon exposure to light were reported in 1910 by F. C. Brown,³ and termed *light-negative*. Six of these units were made, all of which showed a very low resistance, five hundred to ten ohms, and one had even a less resistance. The sensibility of these units was never above fifteen or twenty per cent.

The discovery of light-negative selenium opened up two new fields of investigation: first, the problem of ascertaining the conditions necessary for the reproduction of such units at will, and second, the determination of the characteristics of those units which were already made.

The method used by Dr. Brown in the production of his light-negative selenium was somewhat as follows: He powdered the black, glassy selenium and placed it upon an ordinary porcelain insulating cleat which had been wound with a double spiral of German silver wire. Enough selenium was placed upon this cleat to give a surface of about two square

¹ "Unit" is used in this paper in preference to "cell."

² Phys.-Zeitschr., Vol. 9, 1908, p. 569.

³ Phys.-Zeitschr., II. (1910), 481, also PHYS. REV., XXXIII, p. 1, 1911.

centimeters. The porcelain was heated in air for perhaps half an hour and then allowed to cool to approximately 100°. It was reheated in a sand bath or oven slowly to about 210° and very slowly cooled. In each case it was taken from the oven when the temperature was not lower than 100°. These units were made by Dr. Brown in the winter and early spring of 1910. My attempt at their reproduction was not begun until the fall of 1910. After three months' work, with the opportunity of counsel with Dr. Brown, and under similar conditions, I was still unable to reproduce light-negative units. I did make one that for a time had an extremely low negative sensibility. Its resistance was about 25,000 ohms. All other units that were crystallized by this method were of very low sensibility. The possible variations in conditions and the length of time required to make one unit conspired to make the search for the proper conditions a tedious one. The conditions essential to the successful manufacture of the light-negative units are yet unknown.

PROBLEM AND METHOD.

In an attempt to get at the real nature of these cells their characteristics were investigated along the following main lines:

1. Variation of conductivity with intensity of incident light.
2. Variation of conductivity with time of exposure.
3. Variation in form of recovery curve with intensity of incident light.
4. Variation in form of recovery curve with time of exposure.

But one of the units at hand (made by Dr. Brown) could be used satisfactorily. Its resistance lay between 280 and 309 ohms. The best readings were all taken when this resistance was from 290 to 295 ohms.

The selenium unit was made one arm of a Wheatstone bridge. The resistances of the arms were approximately equal. The voltage across the selenium was always less than one volt. A sensitive galvanometer with a period of 2.6 seconds was used. It gave a deflection of 2.9 centimeters for each .1 ohm change of resistance in the selenium arm. The source of light was a forty-watt tungsten lamp, mounted upon a photometer bar. This sort of lamp was superior to a carbon lamp because it gave less radiant heat per candle power and showed less fluctuation of candle power with voltage. The constancy of candle power was obtained by constancy of voltage, an approximation sufficiently accurate.

To guard against outside disturbances several precautions were taken. To avoid moisture and sudden changes in temperature, the unit had been placed in a bath of paraffin oil upon manufacture, and was left there. The vessel containing the unit was placed inside a larger vessel, which was all blackened except a space directly in front of the sensitive surface

of the selenium. The two vessels were placed inside a blackened pasteboard box. This box was suspended by a cord to cut off the effect of shocks or jars. To eliminate electrostatic induction, the outside of the box was covered with tin foil. The room was only partially darkened, but the selenium was properly shielded by screens of black paper placed on the photometer bar. Temperature readings were made by a thermometer placed in the oil just above and to the front of the sensitive surface of the selenium. The precautions stated above did not eliminate unsteadiness; in fact, whether or not they were of definite assistance was not ascertained.

With the selenium in the dark, the bridge was balanced as closely as convenient. The deflection was read, and then the light from the lamp, which was at a given distance, was suddenly thrown upon it, and the deflection of the galvanometer read every few seconds during the period of exposure. Periods of exposure lasting one, two, and three minutes were taken, after which the light was suddenly cut off, and in each case the galvanometer deflections were read every few seconds during the first one or two minutes of recovery. Two or three complete sets of readings were taken for each time of exposure at the given distance, and then the lamp was moved out to such a position that the intensity would be one half its first value, and the same operation repeated. The law of inverse squares could be applied without serious error due to area of source. Four such positions of the lamp were used and much time spent in trying to get readings at a fifth position, but the cell had become so unsteady that this could not be conveniently done. The temperatures and initial resistances were recorded for each exposure.

EXPERIMENTAL WORK.

Unsteadiness.—At the outset difficulty was encountered, for the selenium under observation had no definite steady resistance even in the dark. At times there were small rapid variations in resistance, amounting to something like one or two tenths of an ohm in either direction. At other times the unsteadiness of the selenium manifested itself in long gradual shifts of resistance, which might take place in either direction with apparently equal ease. These long steady sweeps might amount to as much as one, two, or even three ohms. If one considers that the largest effect produced by the influence of light was a change of only five tenths of an ohm, the impossibility of taking readings when the cell is in an unsteady state will be apparent.

When work was first begun upon the cell, its periods of instability were not very frequent, and consequently not very annoying, for it was

noted that when the cell remained steady before the light was thrown upon it, it seldom became more unsteady upon exposure. After the selenium had been used for two or three weeks the time between steady periods became longer and longer.

In general, a jar caused an increase in resistance, although it hastened the recovery to dark conductivity after an exposure was made. A sudden change in temperature made the unit extremely unstable, causing the conductivity to change back and forth in a most irregular manner. The temperature changes undergone during the night time may have accounted for the fact that the selenium was found to be more stable in the afternoon. The unsteadiness could scarcely have been due to loose contacts external to the unit.

When all disturbances were guarded against as thoroughly as possible there still remained an instability which must be due to something in the selenium structure itself.

RESULTS.

Light-Negative Action.—In Fig. 1 a portion of the data is plotted. The heavy vertical line indicates the time at which the light was cut off. This figure shows the three-minute exposure curves with the four different intensities of light used. It will be seen that in only a few cases do the curves exactly agree with one another during the exposure, while during the recovery even a wider disagreement is shown. Therefore, before any generalizations could be drawn the mean curve had to be determined.

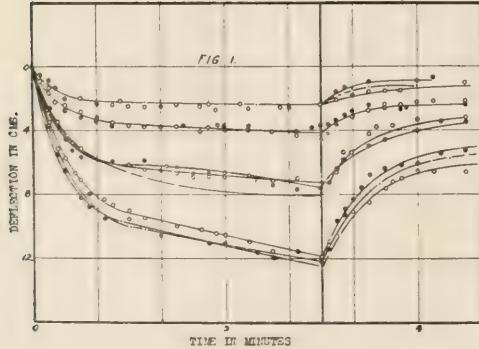


Fig. 1.

Through the points in the curves so drawn, the best smooth curve possible was drawn for each single exposure and recovery, and from these curves the centimeter deflections were read for the times 10, 20, 40, 60, etc., seconds after exposure, and for the same times after the light had been cut off. From these values of the deflection, and from the initial value of the conductivity in the dark, the percentage change of conductivity was computed for each deflection so read. The mean percentage change of conductivity for the given times, at the given intensities, were determined and plotted as the ordinates in the curves of Fig. 2. It is

evident that the deflection after an exposure of one minute should be the same, whether the light were thrown off at the end of that minute or left on for a longer time, and hence for the one-minute curves of Fig. 2 an average has been taken of the percentage change observed during the one-minute exposure, together with the same observed during the first one minute of the two- and three-minute exposures. Likewise, for the two-minute curves an average was taken of the values obtained during the two-minute exposure with those obtained during the first two minutes of the three-minute exposure. Of course this was not possible in case of the recovery curves, so the recovery curves are each simply the average of two or three sets of observations, while, for instance, the one-minute exposure curves are each the average of as many as eight sets of observations.

The curves given in Fig. 2 show several points. The more intense the incident light (the intensities are shown by indicated points in Fig. 3),

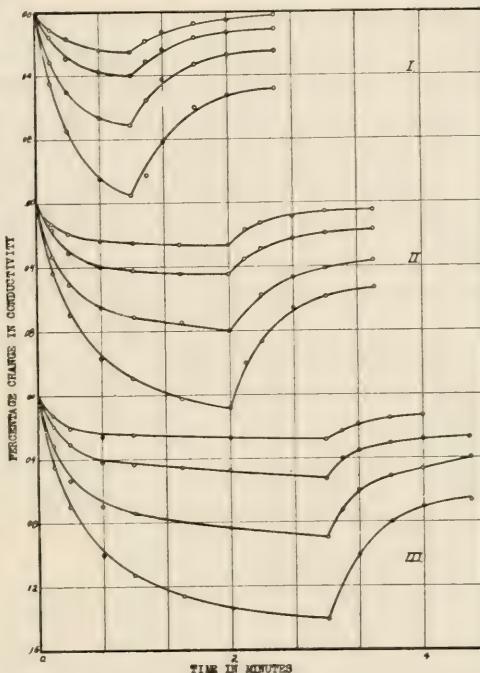


Fig. 2.

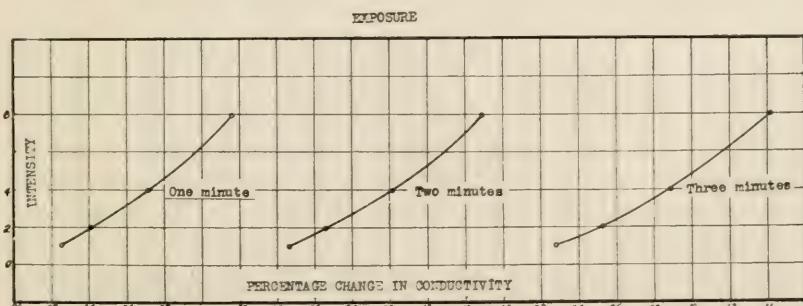


Fig. 3.

the greater is the total change in conductivity for a given period of exposure. With an intensity one half as great the change in conductivity

observed is more than one half as great. The curves of Fig. 3 show the relation between the percentage change of conductivity and the intensity of the incident light, for periods of exposure of one, two, and three minutes respectively.

As to what relations we should have expected from consideration of the light-positive cells it would be hard to say, considering the various formulae that have been established by different investigations.¹

However, I have replotted my curve between change of conductivity at the end of three-minute exposure and intensity, using the distances from the source as abscissæ, so this curve might be compared with a similar one of Carpini reproduced by Ries. Curve I., Fig. 4, is the partial curve on an enlarged scale for the light-positive unit of Carpini, while Curve II. shows the light-negative one used in this investigation.

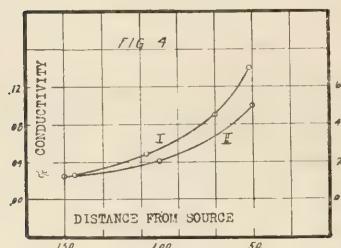


Fig. 4.

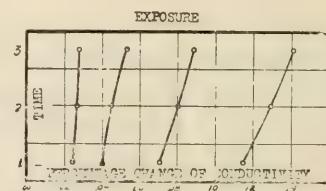


Fig. 5.

The two curves are in general the same shape, in fact, the agreement between the action of the light-negative and that of the light-positive units, under exposure to light of various intensities, is quite as close as that between two samples of light-positive selenium.

We also see that the longer the time of exposure the greater is the total change of conductivity for a given intensity of exposure. The relation between the conductivity change and the time of exposure for the four different intensities investigated are given in the curves of Fig. 5.

Another thing which seems apparent from the shape of the curves is that the less intense the light, the more quickly does a given per cent. of the total change take place, that is, the more quickly does the conductivity-time curve become parallel to the time axis. To show more plainly that this is true the scale to which each curve is plotted has been changed until, at the end of three minutes exposure the change in conductivity, so plotted, comes to the same point for all four intensities.

¹ See Chap. VIII., Ries, *Die Elektrischen Eigenschaften und die Bedeutung des Selens für die Elektrotechnik*.

Curve I., Fig. 6, represents the change produced by the action of the faintest light, while Curve IV. represents that produced by the action of the most intense light.

The recovery curves are seen to be, in general, the reverse of the exposure curves, sloping sharply at first, and then more and more slowly approaching the original value of the conductivity in the dark. The greater has been the total change, the less complete is the recovery within a given time after the light has been cut off. Curves in Fig. 7 show that

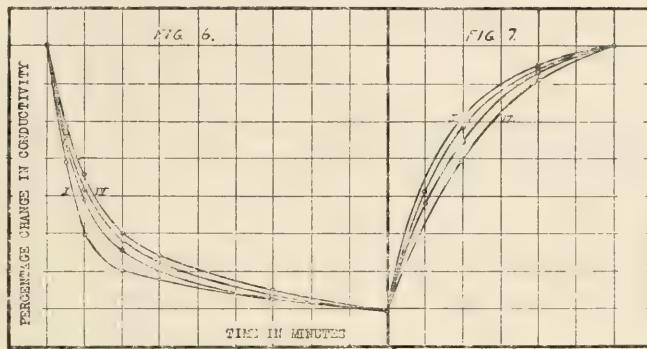


Fig. 6.

Fig. 7.

when the scales of plotting have been reduced, as in Fig. 6, for the exposure curves, that the same per cent. of the total recovery is reached first where the total change has been least. This is an effect similar to that shown in Fig. 6 for exposure to lights of different intensities.

Curve I., Fig. 8, shows the percentage change in conductivity after

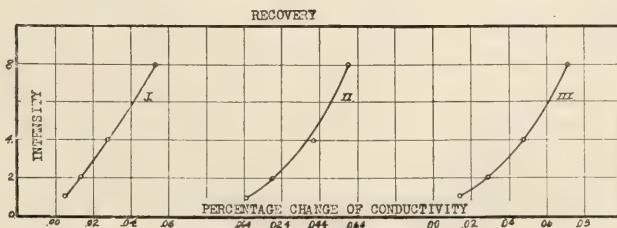


Fig. 8.

the selenium has been allowed to recover for one minute from an exposure of one minute, plotted with the intensity of the light to which it has been exposed. Curves II. and III. show the same for one-minute recoveries from exposures of two and three minutes respectively. These are all long, slightly concave, curves.

The next set of curves shows the percentage change in conductivity after the selenium has been allowed to recover for one minute from an exposure to lights of given intensities, plotted against the time of exposure. Curve IV., Fig. 9, represents the relations for an exposure to the most intense light, while Curve I. represents the same for an exposure to the least intense light. These are also long curves, but are slightly convex.

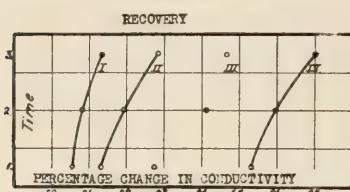
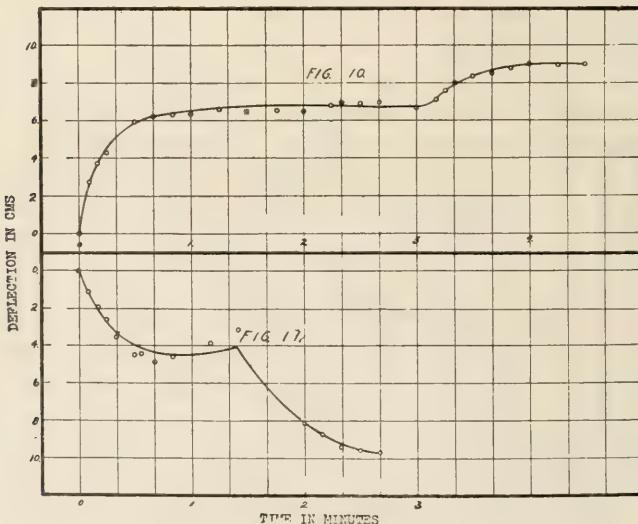


Fig. 9.

negative units with the facts found by Miss Louise McDowell in regard to the Bidwell type of light-positive units. She states¹ "the effect of increased duration of excitation upon the form of recovery curve is similar to the effect of increased intensity."

Light-Positive Action.—When the unit was first put in use several weeks elapsed before it was observed to act at any time as a light-positive



Figs. 10-11.

unit.² But as the work progressed this happened an increasing number of times, until, in all, eleven cases of this light-positive action were recorded. Some of these positive deflections were followed closely. Fig.

¹ PHYSICAL REVIEW, XXIX., p. 35, 1909.

² Brown in an article previously cited reports this light-positive action as occasionally observed in some of the other units.

10 shows the form of one type of action, both after the light has been thrown upon the selenium, and after it has been cut off. The exposure curve is of the form of the regular exposure curves observed with a Ruhmer unit, while the conductivity curve after the light is off reminds one of the recovery curve for the light-negative unit. At least three such cases as this occurred.

After plotting this curve, the occurrence of its exact opposite was recalled, and its appearance watched for. It was never caught, however, except in the case of the partial curve plotted in Fig. 11. Here the exposure curve is of the light-negative form, while the recovery curve is similar to that of the light-positive unit.

One surprising thing about this light positiveness in the light-negative unit is the ease and suddenness with which it comes and goes, leaving no trace of itself. The table below will show this point well.

	Time.	Interval.	Resistance in Ohms.
Fig. 4. Curve II. Negative	5:56	6 min.	291.01
Fig. 10. Positive	6:02	11 min.	290.97
Fig. 4. Curve III. Negative	6:13		290.7

It is seen that a perfectly regular light-negative curve was taken, then within a period of six minutes the light-positive curve of Fig. 10, while within another period of eleven minutes it has regained its former character and gave another perfectly regular light-negative curve.

It seems that all this simply shows how nearly this selenium is existing in the two forms at the same time. In the earlier part of this article we noted how the high resistance selenium had a high sensibility, and how the sensibility decreased with resistance through several types. Now if we can think of the resistance becoming so low that the sensitiveness passes through a zero point, and then to a negative value, we can understand how the units whose negative sensitiveness is as low as that of the one we are discussing, would be existing so close to the border line of sensitiveness that the sudden darkening or lighting might be a sufficient stimulus to throw from one form over into another.

A second unit of resistance close to five hundred ohms was set up, but it was found that it was even more unsteady than the unit of three hundred ohms which had been used. Perhaps this might have been expected, for the higher resistance would seem to indicate that this unit was existing still closer to the border line of sensitiveness than the former one.

Impurities.—The question first asked when the light-positive action of selenium was discovered was whether or not the whole effect was not

due to the presence of an impurity such, perhaps, as a selenide formed by the selenium and the metal of the electrode. Pfund¹ answered this question by making sensitive units using carbon, which will not combine with selenium, as his electrodes.

In the manufacture of his units, Dr. Brown used German silver wire which the selenium attacks to some slight extent, but the cells of Ries which approximate those of Brown were made with carbon electrodes. No attempt has yet been made to manufacture the light-negative units using carbon.

The striking similarity which we find between the action of the light-negative and that of the light-positive selenium makes it probable that this negative effect is due to some peculiar structure of the selenium itself, or due to an impurity which will act in a similar manner to the selenium. It may be that if impurities affect the manufacture of these units they act simply to aid in the formation of the crystals or an arrangement of them such as may be necessary to cause light-negative action. Indeed, this seems the more reasonable, for selenium is unique in its sensibility to light.

Temperature Effect.—In this limited investigation nothing was attempted to show the effect of differences in temperature upon the dark resistance of the selenium, yet with each observation the temperature and dark resistance were both recorded in hope that some correction for temperature might be applied.

So irregular were the relations found between the two that no statement could be made in regard to the variation one with the other, whether we consider all the readings or only those for a single day. Brown² shows that within certain limits the conductivity is increased by a rise of temperature.

SUMMARY.

It is impossible to make any general statements concerning light-negative selenium, but so far as the selenium unit here investigated is concerned, the following conclusions are in agreement with experiment:

I. The making of light-negative selenium seems to require very particular conditions which were not ascertained after several months of effort.

II. The resistance of the light-negative selenium is very unsteady, both in the light and in the dark.

A sudden jar or a sudden change in temperature adds greatly to this unsteadiness.

¹ Phil. Mag., Vol. 7, p. 26, 1904.

² Phys. Rev. XXXIII, p. 1, 1911.

III. The change in conductivity of the light-negative selenium when exposed to light is very small, being less than one per cent.

IV. Exposure Curves:

1. Change of conductivity increases with increased intensity of light, but not proportionately.

2. Change in conductivity increases with time of exposure, rapidly at first, and then reaches a nearly steady condition.

3. With a faint light the larger per cent. of the total change takes place within the first few seconds of exposure.

V. Recovery Curves:

1. In general, they are the reverse of the exposure curves.

2. The more intense the light to which the selenium has been exposed the less complete is the recovery in a given time after the light has been removed.

3. The longer the selenium has been exposed to the light the less complete is its recovery within a given time.

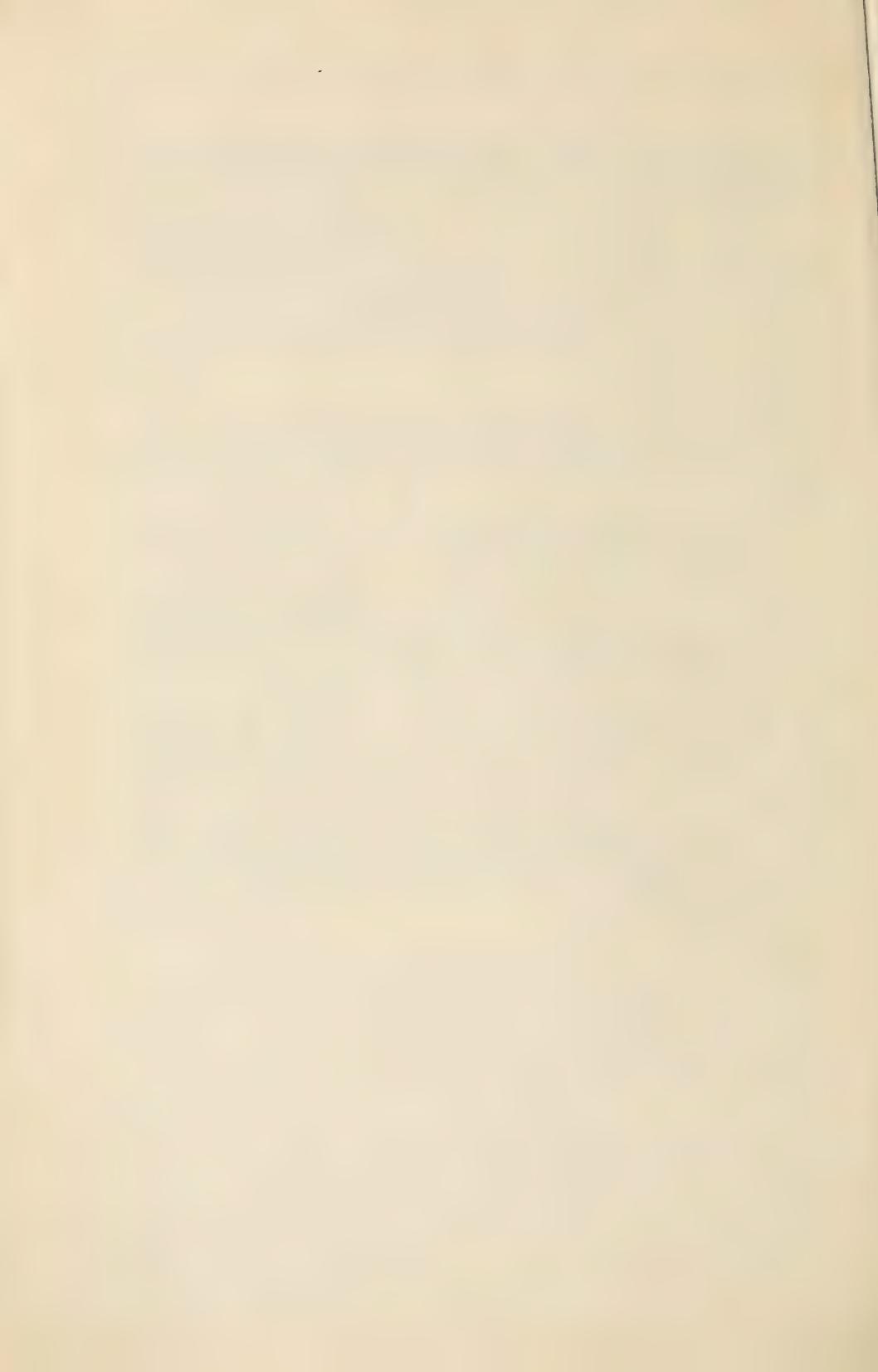
4. The less has been the total change in conductivity during exposure the greater is the per cent. of recovery taking place in a given time.

VI. Sensibility of the light-negative selenium seems to exist so close to the border line of sensitiveness that a slight stimulus will completely change its sign.

VII. The evidence indicates, but does not prove, that the negative effect is due to the selenium structure itself and not to an impurity present.

I wish to express my thanks to Professor G. W. Stewart, under whose supervision these experiments were conducted, and also to Professor F. C. Brown for his kindly interest in the progress of the experiments.

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THE ACOUSTIC SHADOW OF A RIGID SPHERE, WITH CERTAIN APPLICATIONS IN ARCHITECTURAL ACOUSTICS AND AUDITION.

BY G. W. STEWART.

THE discussion in this paper is limited to cases where the source of sound is located on a rigid sphere.

It is an extension of the work of Lord Rayleigh, and had as an incentive a query arising in architectural acoustics.

THEORY.

The medium in which the vibrations occur is assumed to be uniform and to have perfect fluidity. If u , v , and w are the velocities of the particles in the directions of rectangular coördinates, and ρ the density, the equation of continuity is

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0.$$

Let $\rho = \rho_0(1 + s)$, where s is termed "condensation," and insert in the above equation. If we assume the wave length to be long in comparison with the amplitude of vibrations, we can neglect terms similar to $\rho_0 u \frac{\partial s}{\partial x}$ and $\rho_0 s \frac{\partial u}{\partial x}$ in comparison with $\rho_0 \frac{\partial s}{\partial t}$ and $\rho_0 \frac{\partial u}{\partial x}$.

We then have

$$\frac{\partial s}{\partial t} + \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0. \quad (1)$$

From this equation and the assumption that the forces are conservative, Lord Kelvin¹ showed that

$$\frac{D}{Dt} \int (udx + vdy + wdz) = 0.$$

This equation indicates that $(udx + vdy + wdz)$ is a perfect differential. Placing it equal to ψ , we have

$$\frac{\partial \psi}{\partial x} = u, \quad \frac{\partial \psi}{\partial y} = v, \quad \frac{\partial \psi}{\partial z} = w.$$

and ψ is the velocity potential.

¹ Rayleigh, Theory of Sound, Vol. II., page 7.

We have from the general theory,¹ if the impressed forces are zero, a^2 representing $\frac{\partial p}{\partial \rho}$,

$$a^2 s = - \frac{\partial \psi}{\partial t}. \quad (2)$$

If the vibration is assumed simple harmonic, then the velocity and velocity potential are simple harmonic functions. Therefore,

$$\frac{\partial s}{\partial t} = k^2 \psi,$$

where $k = \frac{2\pi}{\text{wave-length}}$ and a is the velocity of sound.

Substituting these values in (1), we have our general equation for aerial vibrations,

$$\frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} + \frac{\partial^2 \psi}{\partial z^2} + k^2 \psi = 0. \quad (3)$$

Expressing (3) in spherical coördinates, and multiplying by r^2 , we have:

$$r^2 \frac{\partial^2 \psi}{\partial r^2} + 2r \frac{\partial \psi}{\partial r} + \frac{1}{\sin \theta} \frac{\partial}{\partial \theta} \left(\sin \theta \frac{\partial \psi}{\partial \theta} \right) + \frac{1}{\sin^2 \theta} \frac{\partial^2 \psi}{\partial \omega^2} + k^2 r^2 \psi = 0. \quad (4)$$

The solution² of this equation is an infinite series, one term of which is

$$\psi_n = \frac{S_n}{r} e^{-ikr} f_n(ikr) + \frac{S_n'}{r} e^{+ikr} f_n(-ikr), \quad (5)$$

where S_n is a spherical surface harmonic of degree n , and

$$\begin{aligned} f_n(ikr) = 1 + \frac{n(n+1)}{2 \cdot ikr} + \frac{(n-1) \cdots (n+2)}{2 \cdot 4 \cdot (ikr)^2} \\ + \frac{(n-2) \cdots (n+3)}{2 \cdot 4 \cdot 6 \cdot (ikr)^3} + \cdots + \frac{1 \cdot 2 \cdot 3 \cdots 2n}{2 \cdot 4 \cdot 6 \cdot 2n (ikr)^n}. \end{aligned} \quad (6)$$

Inasmuch as ψ is assumed a simple harmonic function of the time, we may write

$$\begin{aligned} \psi_n = & \left[\frac{S_n}{r} e^{-ikr} f_n(ikr) + \frac{S_n'}{r} e^{+ikr} f_n(-ikr) \right] e^{ikat} \\ = & \frac{S_n}{r} e^{ik(at-r)} f_n(ikr) + \frac{S_n'}{r} e^{ik(at+r)} f_n(-ikr). \end{aligned} \quad (7)$$

The first term must represent a disturbance travelling outward, and the second a disturbance travelling inward. If we assume a rigid sphere,

¹ Rayleigh, Theory of Sound, Vol. II., p. 15.

² Ibid., p. 237.

and locate the source upon it, the second term disappears, and we have

$$\psi_n = \frac{S_n}{r} e^{ik(at-r)} f_n(ikr). \quad (8)$$

Assume that in the source the velocity is normal to the sphere, the radius of which is c . Let this velocity be represented by $U e^{ikat}$, U being a function of the point considered. U can be expanded in a series of surface spherical harmonics,

$$U = U_0 + U_1 + U_2 + \cdots + U_n + \cdots.$$

When $r = c$,

$$\frac{\partial \psi_n}{\partial r} = U_n e^{ikat},$$

and from (8),

$$\psi_n = -\frac{c^2}{r} e^{ik(at-r+c)} U_n \frac{f_n(ikr)}{F_n(ikc)},$$

where

$$F_n(ikr) = (1 + ikr) f_n(ikr) - ikr f'_n(ikr), \quad (9)$$

and, finally,

$$\psi = -\frac{c^2}{r} e^{ik(at-r+c)} \sum \frac{U_n f_n(ikr)}{F_n(ikc)}. \quad (10)$$

The problem before us is to find the intensity of sound at any point, the sphere being rigid and hence neither absorbing nor transmitting the sound. In as much as our deductions are to be applied to architectural acoustics where the ear is the receiving instrument, we will consider intensity as referring to the potential energy, or energy due to s , the condensation. The reader should be reminded that in this problem, the kinetic energy of the progressive wave is not equal to the potential energy, since, in general, this would be true only of a plane progressive wave. The conditions of the problem preclude the possibility of a plane wave.

It can be easily shown that the energy per unit volume due to a condensation s is $\frac{1}{2} \rho_0 a^2 s^2$ where dp is equal to $\rho_0 s a^2$.¹ Referring now to (2), we have the energy per unit volume or the "intensity" proportional to

$$\left(\frac{\partial \psi}{\partial t} \right)^2.$$

If, now, we wish to compare intensities, we need merely to find the values of the relative intensities by means of the above expression.

Rayleigh² has utilized (10), assuming the source confined to a small

¹ Rayleigh, *ibid.*, p. 15.

² Rayleigh, *ibid.*, page 254. For large values of kc , Rayleigh has put the solution in more convenient form. See *Phil. Trans. of Roy. Soc., A*, 203, p. 87.

area on the sphere in the neighborhood of $\theta = 0$, and obtains the following solution for the relative intensities at a great distance from the center of the sphere:

Relative intensities are proportional to $F^2 + G^2$ where

$$F = \sum \frac{2n+1}{2} \frac{\alpha P_n(\mu)}{\alpha^2 + \beta^2},$$

$$G = \sum \frac{2n+1}{2} \frac{\beta P_n(\mu)}{\alpha^2 + \beta^2},$$

and

$$F(ikc) = \alpha + i\beta.$$

The values of α and β were obtained from (9) and (6).

We shall now consider the case where r is not great, and thus obtain a more general solution of the problem of the acoustic shadow. Equation (10) is simplified if we impose the conditions of our problem upon the general expression for U_n . U_n is the n th term of the surface spherical harmonic series,¹

$$f(\mu, \omega) = \sum_{n=0}^{n=\infty} \left[A_{0,n} P_n(\mu) + \sum_{m=1}^{m=n} (A_{m,n} \cos m\omega + B_{m,n} \sin m\omega) P_n^m(\mu) \right],$$

where

$$A_{0,n} = \frac{2n+1}{4\pi} \int_0^{2\pi} d\omega \int_{-1}^{+1} f(\mu, \omega) P_n(\mu) d\mu,$$

$$A_{m,n} = \frac{2n+1}{2\pi} \frac{(n-m)!}{(n+m)!} \int_0^{2\pi} d\omega \int_{-1}^{+1} f(\mu, \omega) \cos m\omega P_n^m(\mu) d\mu,$$

$$B_{m,n} = \frac{2n+1}{2\pi} \frac{(n-m)!}{(n+m)!} \int_0^{2\pi} d\omega \int_{-1}^{+1} f(\mu, \omega) \sin m\omega P_n^m(\mu) d\mu.$$

If we assume the velocity U to have the same value over the small area where $\mu = 1$, then,

$$f(\mu, \omega) = \sum_0^{n=\infty} \frac{2n+1}{2} P_n(\mu) \int U P_n(\mu) d\mu,$$

since the coefficients $A_{m,n}$ and $B_{m,n}$ become zero.

$P_n(\mu) = 1$, in the region where U is finite; $d\mu = \sin \theta d\theta$; element of area, $dS = 2\pi r^2 \sin \theta d\theta$; therefore,

$$U_n = \frac{1}{2} (2n+1) P_n(\mu) \int U d\mu = \frac{(2n+1)}{4\pi r^2} P_n(\mu) \int \int U dS.$$

Equation (10) therefore becomes

$$\psi = - \frac{e^{ik(at-r+c)}}{2\pi r} \int \int U dS \sum \frac{2n+1}{2} P_n(\mu) \frac{f_n(ikr)}{F_n(ikc)}. \quad (11)$$

¹ Byerly's Fourier's Series and Spherical Harmonics, p. 204, using our symbols.

We shall now proceed to find the relative intensities at a distance r from the center of the sphere, remembering that the relative intensities are proportional to $\dot{\psi}^2$.

From (11),

$$\dot{\psi} = -\frac{ika}{2\pi r} e^{ik(at-r+c)} \iint U dS \sum \frac{2n+1}{2} P_n(\mu) \frac{f_n(ikr)}{F_n(ikc)}.$$

Let

$$\dot{\psi} = -\frac{ika}{2\pi r} e^{ik(at-r+c)} (F + iG) \iint U dS, \quad (12)$$

where

$$F + iG = \sum \frac{2n+1}{2} P_n(\mu) \frac{f_n(ikr)}{F_n(ikc)}. \quad (13)$$

Inasmuch as $\dot{\psi}$ is proportional to the condensation, we may take the real part of (12) which is

$$\dot{\psi} = \frac{ka}{2\pi r} (F \sin \gamma + G \cos \gamma) \iint U dS, \quad (14)$$

where

$$\gamma = k(at - r + c).$$

In determining the intensities, we are concerned only with the average. Taking (14), squaring, and preserving only those terms which contribute to the average value, we have

$$\dot{\psi}^2 = (F^2 + G^2) \left(\frac{ka}{2\pi r} \iint U dS \right)^2.$$

Or, since relative values are desired, and intensity of source is assumed constant, we use the fact that $\dot{\psi}^2$ is proportional to $F^2 + G^2$.

It remains to determine the values of F and G .

Let

$$f_n(ikr) = \alpha' + i\beta', \quad (15)$$

$$F_n(ikc) = \alpha + i\beta. \quad (16)$$

Then according to (13),

$$F + iG = \sum \frac{2n+1}{2} P_n(\mu) \frac{\alpha' + i\beta'}{\alpha + i\beta}.$$

The following must then hold,

$$F = \sum \frac{2n+1}{2} P_n(\mu) \frac{\alpha\alpha' + \beta\beta'}{\alpha^2 + \beta^2}, \quad (17)$$

$$G = \sum \frac{2n+1}{2} P_n(\mu) \frac{\alpha\beta' - \alpha'\beta}{\alpha^2 + \beta^2}. \quad (18)$$

To solve a problem, then, the values of α , α' , β , and β' in (15) and (16) are found by using (6) and (9); the substitution is made in (17) and (18); the relative intensities are then obtained by adding F^2 and G^2 . The

forms of the functions F and f , as far as $n = 6$ are given in the following:

$$F_0(y) = y + 1,$$

$$F_1(y) = y + 2 + 2y^{-1},$$

$$F_2(y) = y + 4 + 9y^{-1} + 9y^{-2},$$

$$F_3(y) = y + 7 + 27y^{-1} + 60y^{-2} + 60y^{-3},$$

$$F_4(y) = y + 11 + 65y^{-1} + 240y^{-2} + 525y^{-3} + 525y^{-4},$$

$$F_5(y) = y + 16 + 135y^{-1} + 735y^{-2} + 2625y^{-3} + 5670y^{-4} + 5670y^{-5},$$

$$F_6(y) = y + 22 + 252y^{-1} + 1890y^{-2} + 9765y^{-3} + 34020y^{-4} \\ + 72765y^{-5} + 72765y^{-6},$$

$$f_0(y) = 1,$$

$$f_1(y) = 1 + y^{-1},$$

$$f_2(y) = 1 + 3y^{-1} + 3y^{-2},$$

$$f_3(y) = 1 + 6y^{-1} + 15y^{-2} + 15y^{-3},$$

$$f_4(y) = 1 + 10y^{-1} + 45y^{-2} + 105y^{-3} + 105y^{-4},$$

$$f_5(y) = 1 + 15y^{-1} + 105y^{-2} + 420y^{-3} + 945y^{-4} + 945y^{-5},$$

$$f_6(y) = 1 + 21y^{-1} + 210y^{-2} + 1260y^{-3} + 4725y^{-4} + 10395y^{-5} \\ + 10395y^{-6}.$$

The procedure is readily carried out if r and the wave length are somewhat larger than c . The desired accuracy can be obtained by taking a sufficient number of terms.

THE VARIATION OF SOUND INTENSITY WITH DIRECTION IN THE NEIGHBORHOOD OF A SPEAKER.

A question arises in architectural acoustics as to the effectiveness of reflecting surfaces in the neighborhood of a speaker, and the preceding theory furnished an opportunity for the computation of intensity in an ideal case which approximates the actual. It is assumed that the speaker is replaced by a rigid sphere, and that the source of sound is confined to the vibration in a small area of the sphere.

For computation, the sphere is assumed to be 60 cm. in circumference,

and the wave length 120 cm., approximately that of middle C. The theory is now applied for a given value of r , the angle θ being made to vary. The accompanying Fig. 1 shows the geometrical relations. θ is zero directly in front of the speaker, and 180° directly in the rear of the speaker (the sphere).

Computations have been made, using the values of c just given, several values of r and the following values of θ : 0° , 30° , 60° , 90° , 120° ,

¹ The forms of the function F are reproduced from Rayleigh's Theory of Sound, Vol. II., p. 238.

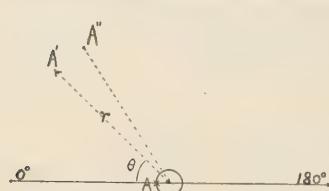


Fig. 1.

150° and 180°. The computations for the distance of 477 cm. ($kc = 0.5$ and $kr = 25$) follow. The values of α , α' , β and β' were obtained by substituting the above values of r and c in (6) and (9), and are shown in Table I.

TABLE I.

n	α	β	α'	β'	$\frac{2n+1}{2}$	$\frac{2n+1}{2}$		
					$\times \frac{\alpha\alpha' + \beta\beta'}{\alpha^2 + \beta^2} = A$	$\times \frac{\alpha\beta' - \alpha'\beta}{\alpha^2 + \beta^2} = B$		
0	+	1.000	+	0.500	+1.0000	0.0000	+0.4000	-.20000
1	+	2.000	-	3.500	+1.0000	-.0400	+.19753	+.31569
2	-	32.00	-	17.500	+.9952	-.1200	-.05589	+.03995
3	-	233.00	+	426.5	+.9760	-.2390	-.004880	-.005340
4	+	7,451	+	4,070.5	+.9282	-.3932	$+3,317 \times 10^{-7}$	$4,187 \times 10^{-7}$
5	+	$8,779 \times 10$	-	$1,607.0 \times 10^2$	+.8344	-.5732	$+2,706 \times 10^{-8}$	$+13,652 \times 10^{-9}$
6	-	$4,120 \times 10^3$	-	$2,250.0 \times 10^3$	+.6759	-.7604	$-3,164 \times 10^{-10}$	$+13,728 \times 10^{-11}$

n	$P_n(\mu)$ $\theta = 0^\circ$	$A \times P_n(\mu)$	$B \times P_n(\mu)$	$P_n(\mu)$ $\theta = 180^\circ$	$A \times P_n(\mu)$	$B \times P_n(\mu)$
				$\theta = 180^\circ$		
0	1.0000	+.40000	-.20000	+.10000	+.40000	-.20000
1	1.0000	+.19753	+.31569	-.10000	-.19753	-.31569
2	1.0000	-.05589	+.03995	+.10000	-.05589	+.03995
3	1.0000	-.00488	-.00534	-.10000	+.00488	+.00534
4	1.0000	+.00033	-.00042	+.10000	+.00033	-.00042
5	1.0000	+.00002	+.00001	-.10000	-.00002	-.00001
6	1.0000	.00000	.00000	+.10000	.00000	.00000
		$+.53711$ $= F$ $F^2 + G^2 = 0.3108.$	$+.14989$ $= G$		$+.15179$ $= F$ $F^2 + G^2 = 0.2446.$	$-.47083$ $= G$

In finding the value of $P_n(\mu)$ for negative values of μ , the relations $P_{2n+1}(90^\circ + \theta) = -P_{2n+1}(90^\circ - \theta)$, and $P_{2n}(90^\circ + \theta) = P_{2n}(90^\circ - \theta)$

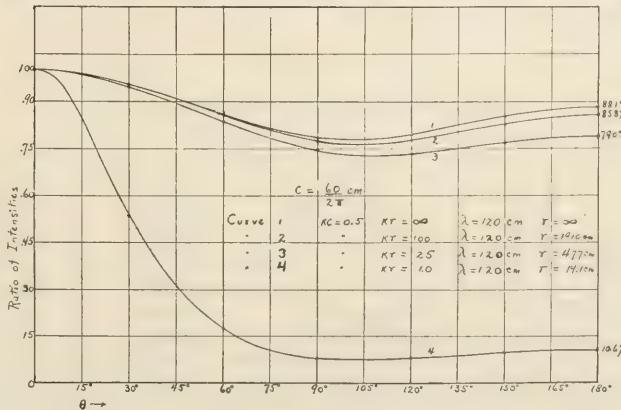


Fig. 2.

were used. The values for $F^2 + G^2$ for the angles not given in the table were found to be 0.294 for 30° , 0.260 for 60° , 0.231 for 90° , 0.277 for 120° , and 0.237 for 150° . These values are plotted in Curve 1, Fig. 2, the one directly in front of the source, $\theta = 0^\circ$, being given the value unity. The other curves exhibit the results for other distances. Of course the computed points are quite widely separated and the curves between them may not be correct. Computations for other angles would be needed if for any purpose greater accuracy is required. When $r = \infty$, the results agree with those obtained by Rayleigh, to which reference has already been made.

The results for two of the distances are again plotted in Fig. 3 for

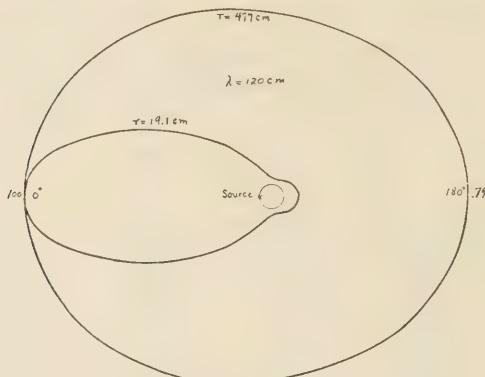


Fig. 3.

clearness. The curves in these figures show the presence of a minimum first mentioned by Lord Rayleigh, the variation with distance, indicating that the shadow is more marked the closer to the sphere (or to the speaker), and the importance of the reflecting surfaces in every direction in the neighborhood of a speaker.

TABLE II.

Wave length, 240 cm., $kc = 0.25$, $kr = 12.5$.

n	α	β	α'	β'
0	+	1.000	+	0.000
1	+	2.000	—	.08
2	—	140.0	—	.24
3	—	953.	+	.4722
4	+	$1,305 \times 10^2$	+	.7463
5	+	$1,439 \times 10^3$	—	.9881

But we need to know what effect is produced by changing the wave length, the distance remaining constant. This effect I have ascertained

Wave length, 60 cm., $kc = 1.0$, $kr = 50$.

n	α	β	α'	β'
0	+	1.000	+	1.000
1	+	2.000	-	1.000
2	-	5.000	-	8.000
3	-	53.00	+	34.00
4	+	296.0	+	461.0
5	+	4,951	-	3,179

Wave length, 30 cm., $kc = 2.0$, $kr = 100$.

n	α	β	α'	β'
0	+	1.000	+	2.000
1	+	2.000	+	1.000
2	+	1.750	-	2.500
3	-	8.000	-	4.000
4	-	16.19	+	35.12
5	+	186.6	+	85.44
6	+	538.8	-	1,177.3

by adopting wave lengths one octave lower, 240 cm., one octave higher, 60 cm., and two octaves higher, 30 cm. The distance, r , remains 477 cm. The following table gives the values of α , α' , β , and β' for these three additional wave lengths.

The results of computation¹ with the above values are exhibited in

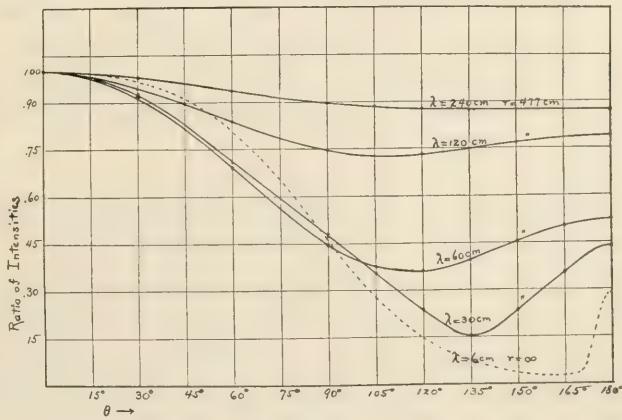


Fig. 4.

the curves of Fig. 4,² together with the values already given for the same distance and 120 cm. wave length.

¹ The computations involved in Figs. 2 and 3 have been very carefully checked and are correct to four significant figures. Those exhibited in Fig. 4 have not been so carefully checked, but are thought to be correct to three significant figures.

² The dotted curve represents Rayleigh's results for $KC = 10$, which are referred to elsewhere.

It is here to be observed that a change in pitch makes a marked difference in the shadow. With the wave length 240 cm. there is no minimum discernible. The variation between the 240 cm. and 120 cm. curves is much less than between the 120 cm. and 60 cm. curves. This shows that the shadows at first change slowly with diminishing wave lengths or sounds of higher pitch. Clearness of enunciation depends largely upon tones considerably higher than the fundamental. It is evident, then, that no curve can be drawn which truly represents the shadow, for the effective shadow (judging by clearness) would be different for different vowels, for different consonants, and hence for different words. We are compelled to leave the matter in this indefinite state, utilizing the curves already exhibited as a general guide. These curves probably limit all others representing the shadows which would occur with the tones in the selected three octaves, so that they give a fair picture of what occurs for that particular range.

Our conclusions are: (1) that an exact statement of the importance of reflecting surfaces in various locations cannot be given, even admitting the approximation involved in the substitution of the sphere for the speaker, for clearness of speech depends upon very complex tones; (2) that the intensity in the rear is generally (not for a wave length of 30 cm.) greater than at any point in the rear hemisphere surrounding the speaker; (3) that the results exhibited in the accompanying curves are sufficiently definite to indicate that the reflecting surfaces at any point in the neighborhood of a speaker are too important to neglect. It is to be noted that the effectiveness of reflecting surfaces is not here being discussed save in so far as that effectiveness is determined by the intensity of sound.

APPARENT INTENSITY OF SOUND FROM A SOURCE AT A DISTANCE AS DEPENDENT UPON THE POSITION OF THE HEAD.

The above topic is of considerable interest because of its bearing upon the perception of sound direction. Rayleigh¹ has discussed the effect of the position of the head upon the ratio of the sound intensities at the two ears, with the source at a distance great in comparison with the wave length of sound. The theory developed in this paper makes possible its application in case the source of sound is not at a great distance. The application is made possible by Helmholtz's reciprocal theorem. This may be stated as follows:²

"If in a space filled with air which is partly bounded by finitely

¹ Rayleigh, *Phil. Mag.*, XIII., 1907, p. 214.

² Rayleigh, *Theory of Sound*, Vol. II., p. 294.

extended fixed bodies and is partly unbounded, sound waves be excited at any point A , the resulting velocity potential at a second point B is the same both in magnitude and phase as it would have been at A had B been the source of sound."

The preceding theory found the relative intensities with varying angle θ at a given distance from the center of the sphere with the source at A (see Fig. 1). Thus the relative intensities at points A' , A'' , etc., were obtained. The reciprocal theorem states that the velocity potential at A , when the same source is removed to A' , is equal to the velocity potential which was formerly at A' . Thus with the source at A' , the velocity potential at any and at all points of the sphere can be ascertained.

Inasmuch as the reciprocal theorem states that the velocity potential is the same in phase as well as magnitude, then the values of $\dot{\psi}$ and $\dot{\psi}^2$ can be considered the same. We can thus use the reciprocal theorem to refer to intensities (due to pressure) as well as to velocity potentials.

The values for intensities will be taken from the curves already exhibited, the assumption being made that the head approximates a rigid sphere, with the ears diametrically opposite. In obtaining the sum¹ of the relative intensities at the ears due to a source of sound at a distance r , we will need to add the values for θ and $(180^\circ + \theta)$. Since the intensity at $(180^\circ + \theta)$ is the same as at $(180^\circ - \theta)$, we will obtain the sum by adding θ and the latter.

The effect of distance upon the apparent intensities will first be considered. In the accompanying Fig. 5 are exhibited the results obtained

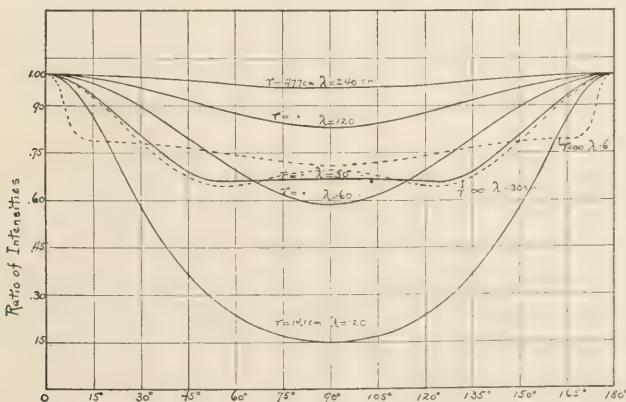


Fig. 5.

¹ The sum of the relative intensities is plotted in preference to the ratio of intensities. Reasons for this will be made clear in a subsequent paper. We here assume that the apparent intensity is the sum of the two intensities, and the relative values of the sum are plotted in Fig. 5. It should be noted that no attention is paid to phase differences.

when the source is at 477 cm., and at 19.1 cm. The curves describe the effect with 180° rotation of the head; although 90° would have been sufficient. The resulting apparent intensity is the greatest when the diameter connecting the ears is in the direction of the sound source. Also, the variation of the apparent intensity with the position of the head is more marked the nearer the source to the hearer, the maximum intensity being sharper and the maximum variation greater.

In Fig. 5 are also exhibited the relative apparent intensities for the wave lengths 240 cm., 60 cm., and 30 cm. Here are also represented by the dotted lines the results of Rayleigh¹ for $kc = 2$ (wave length 30 cm.), and $kc = 10$ (wave length 6 cm.), r being considered infinite in both cases. It is evident that in each case the position of the maximum apparent intensity is that of 0° – 180° , or the ear toward the source. Furthermore, the maximum apparent intensity is more sharply marked as the pitch of the sound becomes higher.

The fact that the position of the minimum does not remain at 90° with decreasing wave length is somewhat surprising. A reference to Fig. 4 and a recognition of the movement of the minimum intensity toward 180° , shows why the apparent intensity in the 90° position should not continue to be a minimum with increasing frequency.

As pointed out by Rayleigh, one of the factors of importance in the location of the source of sound is the variation of apparent intensity with the position of the head. The evidence from these curves would be that for low tones, the intensity factor is not very effective, for the apparent intensity is almost the same in any position. With tones somewhat higher, this factor would seem to become more effective. But with tones still higher, wave length 30 cm. and less, its importance again diminishes. The dotted lines can be considered as an approximate representation of what occurs at the wave lengths stated and a distance of 477 cm.

The foregoing results are obviously only approximate, for we have assumed the head to be equivalent to a rigid sphere with the ears diametrically opposite. With this limitation we can conclude: (1) that the apparent intensity is always greatest when the head is turned with an ear toward the source, the 0° – 180° position; (2) that the variation of the apparent intensity with the position of the head is more marked the nearer the source to the hearer; (3) that with decreasing wave length the maximum value of apparent intensity occurs with greater sharpness; (4) that the maximum variation of apparent intensity is least with lowest tones; (5) that the maximum variation of apparent intensity does

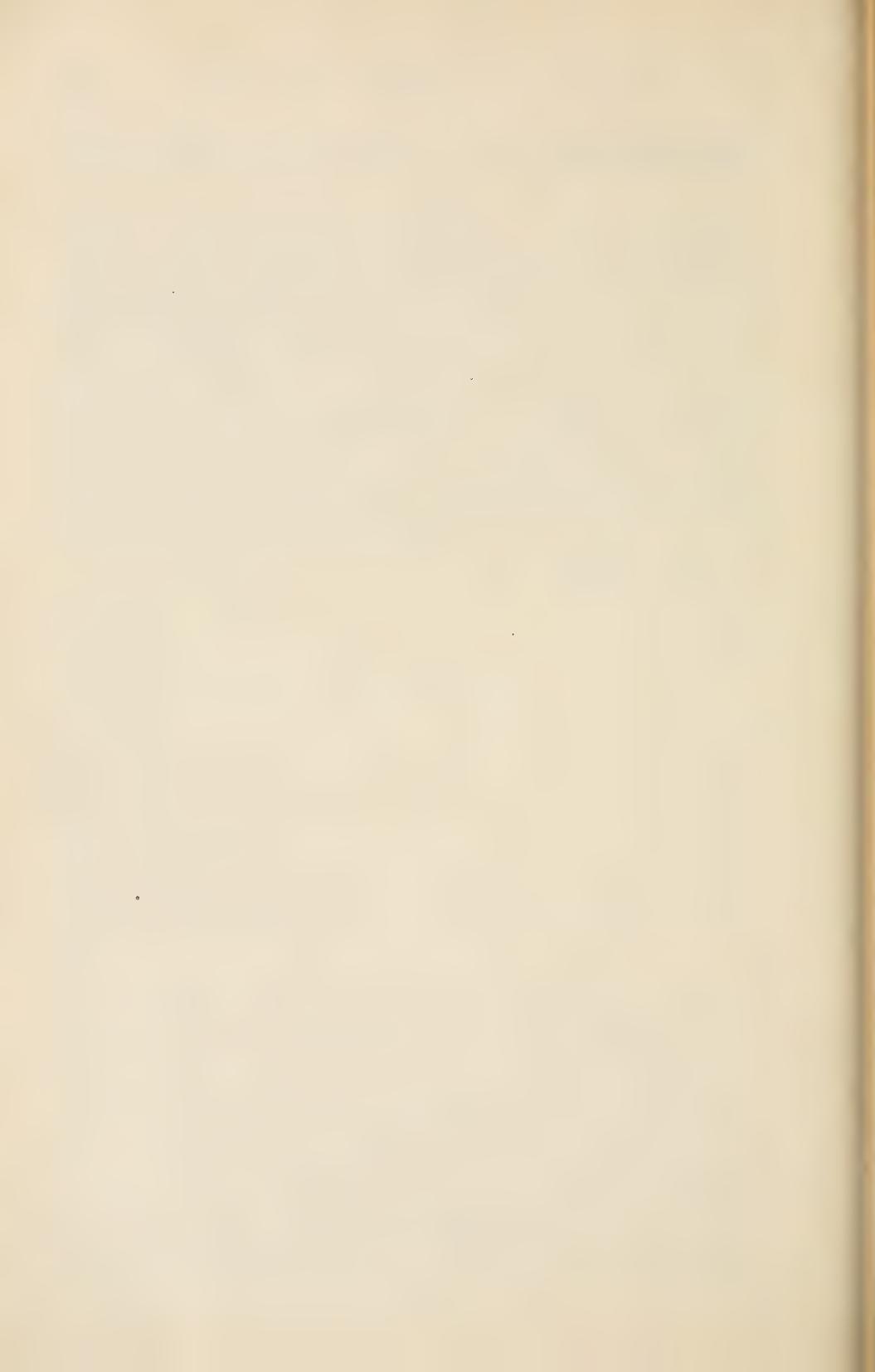
¹ Rayleigh, Phil. Trans. Roy. Soc., A, 203, p. 87.

not increase without limit, for at wave length 30 cm. it has already commenced to decrease.

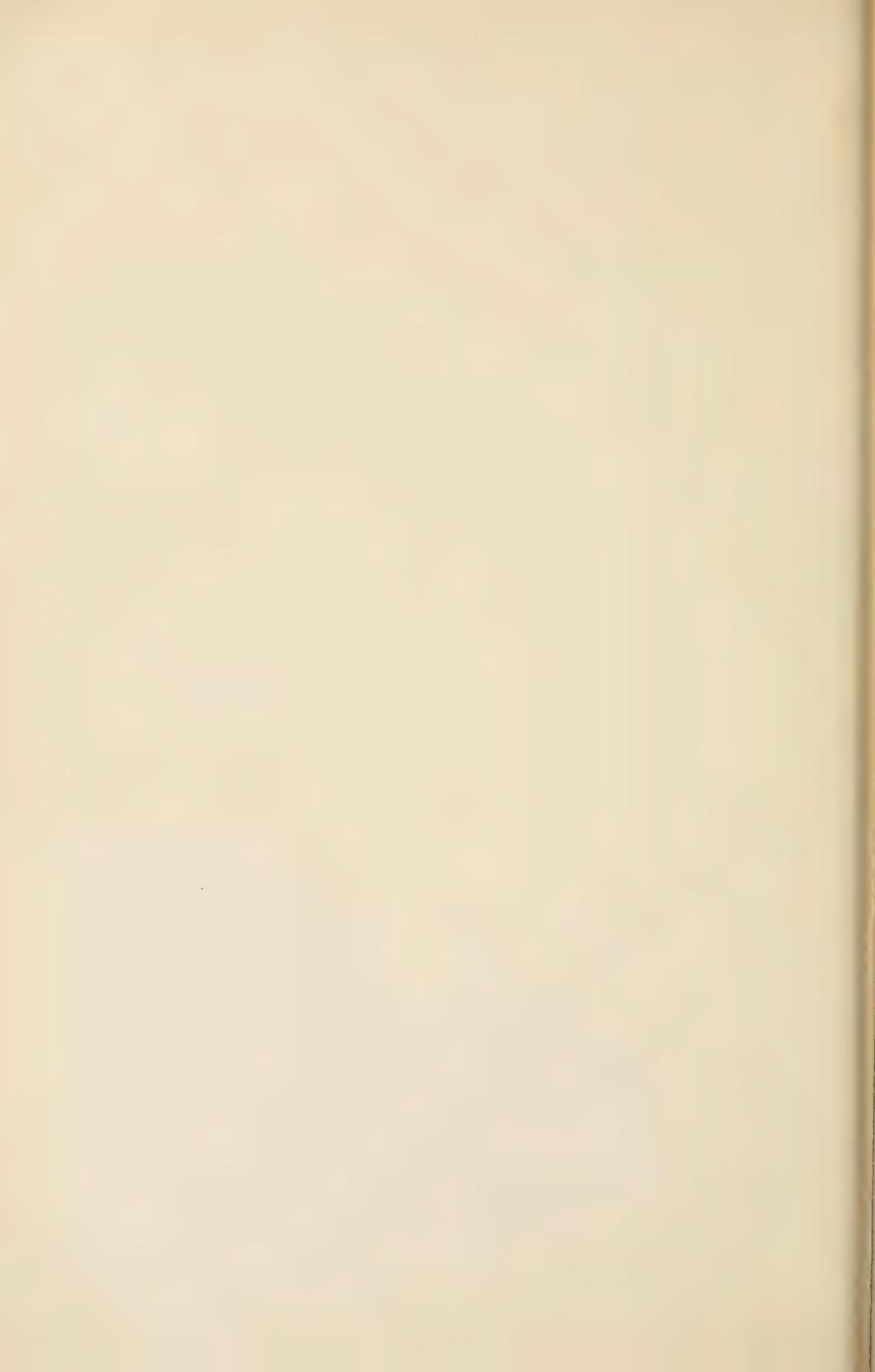
SUMMARY.

This paper discusses the acoustic shadow of a rigid sphere in terms of intensities due to pressures, when the source is located on the sphere and when the distances at which the intensities are determined are not large in comparison with the sphere. The analysis of the problem is presented and two applications of the solution are presented: (1) the effectiveness of reflecting surfaces when placed in various positions in the neighborhood of a speaker, the effectiveness being judged by the intensities only; (2) the apparent intensities of sound from a source at a distance as dependent upon the position of the head, which is of interest because of its bearing upon the perception of the direction of sound. The conclusions are presented with sufficient brevity under the topics discussed.

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THE EFFECTIVE DEPTH OF PENETRATION OF SELENIUM BY LIGHT.

BY F. C. BROWN.

RECENTLY it was shown that¹ the changes of conductivity in a certain variety of selenium could be explained quite accurately by assuming that the light penetrates throughout the conducting layer and that it produces two changes in the selenium. If, therefore, the light action takes place in only a very small portion of the conducting layer, it might be necessary to recheck theory and experiment. The principal object of this investigation was to get the effective depth of penetration in order to be more certain of the theory. Incidentally the results give some information bearing on the nature of the process of absorption in this variety of light-sensitive selenium.

THEORETICAL CONSIDERATIONS.

The measurements on the depth of penetration depend on the similarity of heat and light action in selenium. In fact in so far as temperature changes do not produce effects in the selenium identical to the light changes, the results will be in error. The reasons for assuming the identity of the two actions will be given in a succeeding paragraph. The theory is much simplified by calculating with conductivity relations rather than with the resistance relations. In fact I believe that many times we are handicapped in theoretical considerations by placing too much emphasis on Ohm's Law. Further the theory requires a second assumption, which is that temperature changes take place throughout the conducting layers of selenium alike everywhere. The results will be indirect in that they depend on the two assumptions just mentioned. Naturally, if light acts the same as an increase of temperature, we should expect that the absolute amount of change in the conductivity, by a light of constant intensity, would diminish as the temperature of the selenium rises. Thus if a curve is plotted showing the absolute change of conductivity, ΔC , for the various values of the conductivity, C , we have the relation between C and ΔC regardless of the depth of penetration of

¹ Paper by Brown on "The Recovery of the Giltay Selenium Cell and the Nature of Light Action in Selenium."

the light. Suppose the curve in Fig. 1 to represent such relations as just mentioned. Suppose the conducting layer of selenium at temperatures T_1, T_2, T_3 , etc., to have conductivities of C_1, C_2, C_3 , etc., respectively, at the various temperatures. The amount of change in conductivity by the standard light, or the absolute sensibility, is given by the ordinates at

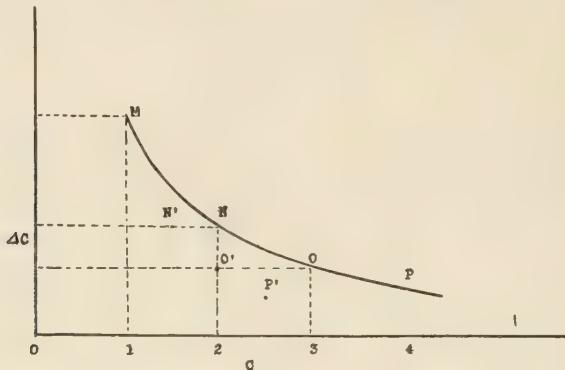


Fig. 1.

the points M, N, O and P for the same temperatures. However the absolute sensibility is given as a function of the conductivity prevailing before the standard light illuminates the selenium. Temperature changes are introduced only as a means of producing uniform changes in the conductivity that reach to the bottom of the selenium. For the sake of argument, consider the selenium divided into two imaginary layers of equal depth. The plane of these layers is taken perpendicular to the direction of the impinging light. We consider that the effect of the light is everywhere uniform in the top layer, and that there is no action whatever by the light in the lower layer.

The ordinate at N shows the sensibility, ΔC , when the initial conductivity has been doubled. If however the initial conductivity is doubled by light action from a second variable light source, *i. e.*, the intensity of the light is varied until the desired conductivity is attained at the equilibrium condition, then the part of the selenium affected by the light must have been trebled; for

$$C = \frac{1}{2} + 3 \times \frac{1}{2} = 2.$$

But the curve M, N, O, P shows that if the region affected by light is trebled that the sensibility is only what is represented by the ordinate at O . The meaning of this is that if light is used to produce the initial desired conductivity which is double that in the dark, then the point on the sensibility curve will drop from N to O' . Exactly the same method of procedure will locate the points N' and P' , so that we are enabled to plot

the sensibility curve M, N', O', P' , for the selenium when the initial conductivity is altered solely by light. Now if it is found experimentally that the sensibility represented by the curve M, N, O, P , when the initial conductivity is changed by the temperature of the selenium, and if the experiments show that the sensibility is represented by the curve, M, N', O', P' , when the initial conductivity is changed by light, it can be concluded that the effective depth of penetration is one half the total depth of the conducting selenium. However, if the experimental sensibility curve, when all changes are produced by light, lies between the two curves mapped out in Fig. 1, it is to be concluded that the effective penetration is greater than the half depth, and if the experimental curve lies on the other side of M, N', O', P' , the penetration is less than the half depth. Just what fraction of the selenium is penetrated by the light can be determined by finding the theoretical curve that matches the experimental curve. This cut and try method of fitting is not as difficult as it might seem. A very little work will approximately locate the theoretical curve that matches the observations. Other curves may be located in the same way that the one passing through M, N', O', P' , was located.

If the two basic assumptions should be seriously in error, then it might be impossible to match any of the experimental curves with any of the theoretical curves. The curves would not be of the same character, and consequently they would cross each other. The likeness or unlikeness of the character of the experimental and theoretical curves is evidence for or against the original assumptions.

THE SIMILARITY OF HEAT AND LIGHT ACTION.

The experiments are based on the similarity of heat and light action in selenium. In 1908 it was suggested¹ that increased temperature and illumination each seemed to take the selenium toward the same equilibrium state, and it was inferred that heat and light produce the same kind of change in the selenium. Later by a study of the change of conductivity with time when certain selenium cells were suddenly heated or illuminated, MacDowell² concluded that the "action of light and heat in producing change in conductivity in selenium are apparently identical." More recently in an analytical investigation of the time changes in the Giltay cell,³ it was shown that so far as light action is concerned heat alters the direct rates α_1 and β_1 in about the same ratio as does weak illumination and in addition produces a minor change in the reverse rate

¹ Paper by Brown and Stebbins, *PHYS. REV.*, XXVI., p. 273, 1908.

² Paper by Miss Louise MacDowell, *PHYS. REV.*, XXXI., p. 524, 1910.

³ *PHYS. REV.*, XXXII., p. 403, 1911.

β_2 . A further study of the heat changes in selenium indicates with considerable certainty that heat produces the same very rapid and very slow changes as light, and further that there are one or more minor changes that are not caused by light. The first assumption then will be slightly in error owing to the inexact identity of light action and heat action.

The curves in Fig. 2 show the changes in conductivity when the Giltay selenium cell was suddenly changed in temperature. Curve (a) shows the change when the temperature was suddenly raised from 25° C. to

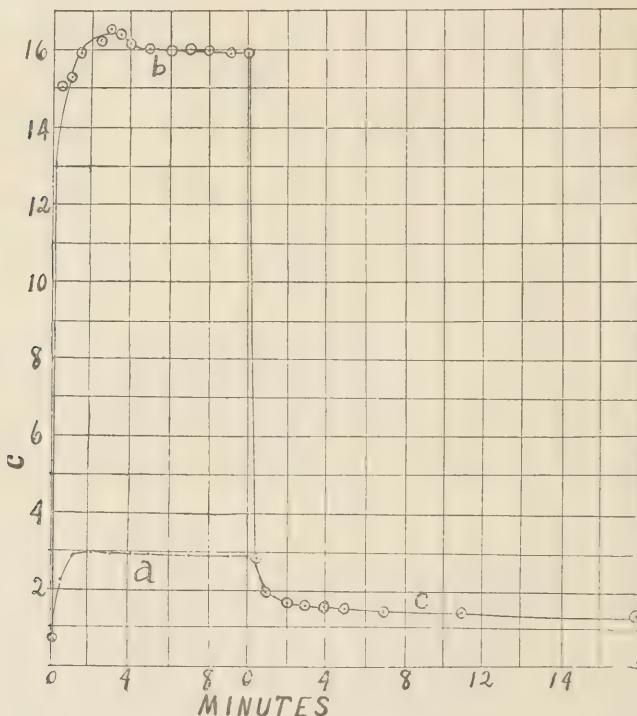


Fig. 2.

Curve (b) shows the change of conductivity of Giltay cell when the temperature was suddenly raised from 25° C. to 93° C. Curve (c) shows the change when temperature change was of the same magnitude but in the opposite direction. Curve (a) is for the sudden change of temperature from 25° C. to 53° C.

53° C. by plunging the cell in a kerosene bath at the higher temperature. Similarly curve (b) shows the changes when the cell was suddenly plunged in a bath at 93° C., and curve (c) is for the recovery when the cell was returned to the bath at 28° C. If these curves are compared with corresponding exposure and recovery curves for light as shown in Figs. 2 and 3

of my former paper¹ it will be observed that there is a striking similarity. For either light or heat about 95 per cent. of the change takes place in less than 30 seconds. It is impossible to be very certain about what portion of the change by heat takes place in very short intervals of time, because of the time required for the selenium to arrive at uniform temperature. Consequently it is impossible to assign proper rates of change to explain the curves obtained in going from one temperature to another. However a careful study has convinced me that while temperature changes produce effects identical to the effect by light, there is also an additional effect of minor importance which is not covered by our theory.

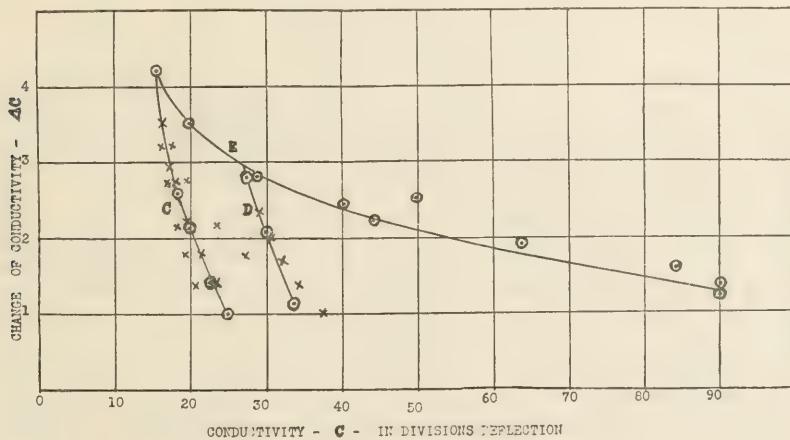


Fig. 3.

This is not manifest in the exposure curve, but the recovery on going from the higher to the lower temperature is very slow, requiring many hours to arrive at the equilibrium value, and the conductivity can not be represented everywhere by an equation having only the sum of two exponential quantities, such as I have presented previously to represent light changes. This lag may arise from changes in pressure on the selenium, arising from a slow changing of shape of the stone form or the wires which are parts of the selenium cell. In fact I think this explanation is very plausible for that small part of the conductivity change which is not covered by our theory.

A similar very slow and very small change in the conductivity has been observed at temperatures above 50° C. by Mr. Ernest Dieterich. After the selenium had been heated to a uniform high temperature for more than an hour and had become apparently constant, it began to increase its conductivity in a rather irregular fashion, the rate being smaller at first,

¹ PHYS. REV., XXXII., p. 406.

reaching a maximum after several hours, and then becoming zero. The total amount of this increase was not more than 10 per cent. of the original conductivity. This too was probably due to an annealing process taking place in the stone cell form. Such a change as the one just mentioned might minimize the falling off of conductivity with heating such as occurs after two or three minutes. It must be understood however that this falling off by temperature rise is not at all necessary in order that light action and temperature action shall be alike, and further that all these dissimilarities are small comparatively and of minor importance.

EXPERIMENTAL ARRANGEMENTS.

The selenium that was used in this investigation was that of the same Giltay cell heretofore mentioned. The selenium was crystallized between two parallel wires of 0.16 mm. diameter wound around the flat stone form. The average depth of the selenium was estimated to be not less than 0.08 mm. and not more than 0.14 mm., the most probable value being 0.11 mm. The cell was placed in a large kerosene bath with stirrer. The temperature of the bath was regulated by an electric heating coil placed in it. Two miniature incandescent lamps inside a beaker were sunk in the kerosene at a distance of about 15 cm. from the selenium. One of the lamps was regarded as a standard and it was always regulated to give a constant light intensity by adjusting the heating current to 0.32 ampere. The second lamp was regarded as a variable light source, and its intensity was regulated by the current so as to produce desired values of the conductivity of the selenium. The intensity of these lights was at all times small compared to a standard candle at a distance of a meter. As there seemed to be no reason for knowing their candle power it was not determined.

The conductivity was measured directly by a Siemens and Halske needle galvanometer in series with the selenium cell. Its sensibility was approximately 2×10^{-7} amperes per division and its resistance was 220 ohms. The range was suitably altered by a shunted resistance.

In these experiments we always intended to measure only the equilibrium values of the conductivity. Consequently the rates of change were observed only with a rather general interest.

THE RESULTS.

The manipulation was quite simple, and can be clearly understood by studying the accompanying Table I., which gives a sample of the observations. A glass heavily coated with anilin blue was placed in the beaker with the lamps so that an approximately monochromatic illumina-

tion of the selenium might be obtained. The conductivity in the dark, C_d , was first measured and then the cell was exposed to the standard light, l , by closing the lamp circuit with 0.32 ampere. Thereby the conductivity increased by an amount ΔC and reached the equilibrium value C_L . After the selenium had recovered its conductivity in the dark, C_d , it was exposed to such a faint illumination from the second lamp that the equilibrium conductivity assumed the desired value C_L . Then the selenium was simultaneously illuminated by the standard, and the conductivity increased to the value C_{L+1} . And so on the variable light was increased step by step while the standard remained fixed.

TABLE I.
Observations with Blue Light.

Time of Observation.	Temperature, Degrees Centigrade.	Conductivity in Dark, C_d .	C_L	C_L or C_{L+1}	ΔC	C
11:13-11:32 A.M.	21.3	15.3	15.3	17.7	2.4	15.3
	21.5	"	17.8	19.2	1.4	17.8
	"	"	16.4	18.4	2.0	16.4
	"	"	20.0	21.1	1.1	20.0
12:50- 1:05 P.M.	"	"	24.0	24.6	0.6	24.0
2:35- 2:50 P.M.	35.8	29.0	—	30.5	1.5	29.0
3:55- 4:10 "	41.6	38.3	—	39.8	1.5	38.3
5:00- 5:10 "	45.6	47.1	—	48.2	1.1	47.1
5:23-	45.6	47.1	—	—	—	—
5:55- 6:02 "	—	44.7	—	45.9	1.2	44.7
7:50-	"	43.3	—	44.5	1.2	43.3
8:00- A.M.	24.0	18.4	—	20.5	2.1	18.4
10:40-11:02 "	37.0	{31.3 30.3}	—	32.4	1.6	30.8

By obtaining sufficient data of this kind, it was possible to plot the sensibility-conductivity curve, A , shown in Fig. 4. This curve merely shows the absolute amount of change of conductivity, ΔC , when the selenium has various initial conductivities. It is understood, in this instance, that the initial conductivity is varied solely by illumination. When the initial conductivity was varied solely by temperature changes, the absolute amount of change by the standard light was not

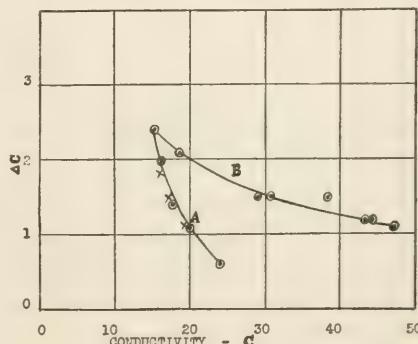


Fig. 4.

notably different as shown in the table and also by curve *B*, of Fig. 2. Considering the possible sources of error, the points lie on a curve as nearly as could be expected. The value of ΔC when C was 38.3 is manifestly too large. Possibly the conductivity was increasing due to temperature action during exposure. It is unfortunate that the conductivity in the dark could not always have been read both before and after exposure to light.

In a similar manner to that just described were the data taken for the absolute sensibility when the selenium was illuminated with red light. Curve *C* in Fig. 3 gives the sensibility when the conductivity was varied by the variable light, but there is a decided difference in the magnitude of the change by the standard light. This is no doubt due to the greater effectiveness of red light in causing change of resistance of selenium.¹ The current in the standard lamp was kept at 0.32 ampere at all times. The curve *D* was obtained from data taken in the same way as those for curve *C*, except that the initial conductivity was kept at $C_d = 27.5$, by keeping the temperature of the cell and its bath at 32° C. The observations shown in curve *E* were obtained as were those in curve *B* of Fig. 4. They are not particularly good but at the higher temperatures a number of difficulties made it hard to obtain the increment of conductivity by the standard light and at the same time keep other conditions fixed. It is believed that the temperature rise during exposure would account for some of the high values obtained.

In working up the results the method of procedure is to assume different depths of penetration and to solve for the corresponding theoretical absolute sensibility curves. The curve that most nearly coincides with the experimental curve is adopted. For illustration consider the curves *C* and *E*, in Fig. 3. First divide the selenium into four imaginary layers, supposing that the light acts as though it penetrated uniformly to the bottom of the first layer. This is equivalent to saying that in the selenium there are four equal parallel conductors, all of which are affected alike by temperature and only one of which is altered by light. The initial conductivity is 15.8. Since curve *E* is taken from temperature variations it shows that when the conductivity of all the selenium and consequently that of the top layer is doubled, that the change of conductivity by the standard light is 2.75 instead of 4.2 as it was at the start. The conductivity of each of the four layers is 3.95. If the top

¹ See paper by Pfund, *Phys. Rev.*, XXVIII., p. 324, 1909, also paper by Stebbins in *Astrophys. Journal*, XXVII., p. 183, 1908, on the color sensibility of selenium, in which he shows that for the Giltay cell there are two maxima instead of one as in the Rulmar cell or the cell used by Pfund.

layer is doubled by the variable light instead of by heat, the three remaining layers will be unchanged and the total conductivity will be

$$C = 3.95 + 3.95 + 3.95 + 2 \times 3.95 = 19.75,$$

and the change of conductivity by the standard light will obviously be $\Delta C = 2.75$. This point is indicated by the cross to the right of curve *C*. Further if the conductivity of all the layers is trebled, making a total of 57.4, the sensibility by the standard light is shown on curve *E* to be 2.17, and if the top layer is trebled by light, the total conductivity before exposure to the standard light is

$$C = 3.95 + 3.95 + 3.95 + 3 \times 3.95 = 23.70.$$

By the standard light this value is increased by the amount $\Delta C = 2.17$. This point is also shown to the right of curve *C*. And so on as many points as desired can be obtained for the theoretical curve when the light penetrates one fourth the depth of the conducting selenium.

By the same identical method theoretical curves for the absolute sensibility when the initial conductivity is varied by light can be obtained for any number of layers of selenium. The crosses to the left of curve *C* mark out such a theoretical curve when 12 layers are imagined, and those crosses that fall on curve *C* are those that obtain if it is supposed that there are 8 layers of selenium and that the effect of light penetrates to the bottom of the first layer. The conclusion here is that the effective penetration of red light is about one eighth of the total depth of the conducting selenium. Curves *D* and *E* when taken together show within the limits of experimental error that the red light penetrated one eighth the depth of the selenium when the initial conductivity is about double what it was at 21.5° C. The importance of this result, that the penetration is almost if not entirely independent of the conductivity, will be considered in the discussion.

The penetration by the blue light is the same as that by the red light. The crosses following curve *A* in Fig. 4 are obtained from curve *B* by supposing eight layers of selenium. These results are reliable probably within about ten per cent. It is worth comparing the sensibility curve for red light with the one for blue light. Curve *E* shows that when the conductivity is doubled that the sensibility is decreased 48 per cent., while curve *B* shows for doubling a decrease of 42 per cent. Just what the significance of this difference may be is not certain, but most probably it arises from experimental errors.

It will be shown in the succeeding paragraphs that all of the selenium in the Giltay cell is conducting and light-sensitive. The total depth of the selenium was estimated as previously stated to be 0.11 mm. One

eighth of this 0.014 mm. This result may look surprisingly large, but I believe that any discrepancies that may arise because of the inexact identity of heat and light action, are in favor of giving a larger result rather than a smaller one. The reader may think this conclusion is obvious, but because of the complexity of temperature action it is very difficult to prove.

THE EFFECT OF REMOVING THE SURFACE OF THE SELENIUM.

The result for the effective penetration, viz., .014 mm., that was stated in the last paragraph depended on the uniform structure of the selenium from top to bottom. It was to obtain information on this point that the surface of the selenium was filed away, and the conductivity and light-sensitiveness of the remaining portion was tested.

The first test was very crude. I took a piece of an old Giltay cell and by the use of a fine Swiss file, I carefully removed the selenium from the wires. It was noted that the cell was conducting until all the selenium was taken off, and that the selenium was light-sensitive even at the very bottom. The second test was a more careful investigation into the effects of filing. This time the selenium between eight parallel wires was considered. The total amount of the selenium was estimated at .06 gm. The conductivity in the dark was 87 mm. After filing away a small amount of selenium from all over the surface, I was greatly surprised to find that instead of the conductivity decreasing because of the slightly smaller cross sectional area, that it had actually increased about five fold. After 24 hours it still showed most if not all of this increased conductivity. It seemed that the filing had changed the properties of the selenium in such a manner as to increase its specific conductivity. After further removing what was estimated to be fully one half of the selenium, the conductivity fell to 170 mm. in the dark, which was however twice larger than what it was before any selenium was filed away. When 20 cm. from a 4 c.p. lamp the conductivity increased to somewhat more than 500 mm.

The third time the selenium was filed gave a conductivity of 90 mm. in the dark and more than 500 mm. in the light. By the fourth filing about 0.02 gm. of selenium was removed, and as far as the eye could detect there was almost no selenium left. However the conductivity was more than 43 mm. in the dark and more than 500 in the light. After 24 hours the conductivity in the dark fell to 20 mm. and when left for 20 seconds one cm. from a 16 c.p. lamp the conductivity increased sixty-six times. The maximum amount of selenium that could have been left was not more than one tenth of what was originally on the

part of the cell considered. These experiments indicate the following facts:

1. That filing changes the properties of the selenium so as to increase its conductivity, and that this at first lowered the relative sensibility to light.
2. By continued filing the relative sensibility, *i. e.*, the ratio of the conductivity in the light to that in the dark, increases.
3. All the selenium on the Giltay cell is conducting, and light-sensitive.
4. That further experiments must be carried on by carefully weighing the selenium removed by each filing in order to determine whether the filing produces a surface action or whether it is more deep seated.

The results that have just been stated were checked with a third sample of the cell, by filing away the selenium in three instalments. The following Table II. gives the results of the observations. In these the light intensity was kept quite constant in the comparative observations, although its value was not determined.

TABLE II.

Time of Observation.	Dec. 16, 10:00 A. M.	12:05 P. M.	12:24.	1:25.	10:30.	Dec. 17.	Dec. 18.
Conductivity in dark.....	4.2	9.6	10.	7.6	3	4	0.7
Conductivity with faint light.....	62.	100.	90.	75.	90.		
By intense illumination.....	85.	135.	118.	98.	130.	135.	20.
Comments.....		Some selenium filed off of entire surface.	Probably half of the selenium removed.	After resting since 12:30			After filing away a least $\frac{9}{10}$ of selenium.

If it is a fact, as the table indicates, that the conductivity did not change by separate filings very much after the first filing until nearly all the selenium was removed, then it is certain that the filing produces essentially a surface action.

Just twelve days after I had made the second set of observations just recorded, I received a letter from Mr. J. W. Giltay in which he described an experiment of the same nature as my filing experiment and which showed essentially the same result. A cell of 190,000 ohms resistance and sensibility 22 to 1 was exposed to a sand blast. Instead of the resistance increasing as he expected because of the removal of some of the selenium, it decreased to 70,000 ohms, and the sensibility became

only 8 to 1. After 15 days the resistance increased to 140,000 ohms and the sensibility to 25 to 1. The temperature was not read, but the resistance and sensibility of a second cell, which was treated like the first in all ways except that it was not subjected to the sand blast, indicated that at least a part of the apparent recovery during the 15 days was due to temperature change. Mr. Giltay states that this experiment seems to prove that the dark resistance was lowered by the sand blast, and also that the sensitiveness was lowered the same as by heating a cell. He attributes the effect to a possible action of the blast of a nature to alter the crystalline structure of the selenium.

THE DISCUSSION OF RESULTS.

It is perhaps safe to place as much confidence in the comparative determinations with different wave-lengths and with the selenium at different temperatures as is placed in the value of the absolute penetration. Whatever error may accrue in the determination of the absolute effective penetration because of the dissimilarity of heat and light action, would obviously be very much reduced in any comparative measurements by the same method. Therefore it is worth while to inquire into the significance of the comparative results.

The penetration by either red or blue light is practically the same. This conclusion would hardly be altered even if we regarded the difference in the falling off of the sensibility by red and blue light as due to experimental errors. If the curve *E* were reduced and substituted for curve *B*, the theoretical conductivity-sensibility curves for light would lie about as much to the right of the experimental curve as they now lie to the left of it.

It is generally expected that the penetration should increase with the increased wave-length. Pfund¹ showed for a thin film of a certain metallic variety of selenium that the absorption for light of $600\mu\mu$ was more than twice what it was for $700\mu\mu$. But we can not compare our result with his because the selenium used by him was a different variety from that found in the Giltay cell. Further the meaning of effective depth of penetration is not the same as maximum depth of penetration. It is quite possible that the effect of light goes much deeper than does the light itself. This would happen if there were any interconnected mechanisms reaching from the surface to the effective depth of penetration. Light would disturb one part and the disturbance would be felt equally throughout the region. Or the mechanism reached by light might extend throughout the selenium, in which case the disturbance would be greatest

¹ Paper already referred to.

at the surface and would diminish with increased depth, so that the effect would be the same as a uniform disturbance extending 0.014 mm. into the selenium. A single crystal in the selenium might include the mechanism, or the mechanism might be included in several crystals. It is perhaps useless to speculate further on the possible mechanism that would permit the effect of the light to penetrate deeper than the light itself. But if the view is correct then we should rather expect any agency that acts on the surface of the selenium to effect the selenium to about the same depth. Thus red light or blue light should effect the selenium to the same depth providing the light itself does not reach into the effected layer but relatively a short distance. This is probably the most reasonable explanation of the matter. If light should really have an average penetration equal to one eighth of the selenium thickness, then one might expect a small fraction of the light to penetrate entirely through the selenium. This was tried, roughly, however, with a negative result.

The results further show that the effective penetration does not vary with the conductivity. Supposing the conductivity to depend on the number of free electrons, then the absorption should vary with the conductivity, providing that the absorption is due to the free electrons as in the case of metals. We can at least say that there is no evidence against the view that the absorption in light-sensitive selenium takes place mostly in the non-conducting, *i. e.*, *A* and *C*, components, and not by the free electrons. I have previously shown that the amounts of the *A* and *C* components are not much altered relatively in the Giltay cell by illumination, while the relative alteration in the amount of the *B* component is very great. Thus we should expect that the penetration should not vary with the conductivity.

The fact that the effective penetration is only one eighth of the thickness of the selenium, will make a difference in the rates of interchange that were found necessary to explain the changes taking place in the Giltay cell,¹ and should therefore make it easier to explain the significance of the rates of change in terms of a few fundamental laws. Particularly the direct rate α_1 should be altered. If I find that making allowance for the incomplete penetration of selenium by light leads to conclusions of importance, I shall hope to get the results in shape for publication.

It seems worth while to investigate further the effect of filing the selenium surface. If the cell does not recover from the filing, it will add evidence on at least two important questions of theory. It will show that the two interchanges that theory has recently shown to exist between the *A* and *B* components and the *B* and *C* components are not

¹ See paper already referred to.

perfectly independent but are rigidly limited perhaps to interactions within given small boundaries, may be crystal boundaries. In addition if a simple mechanical operation such as filing can permanently alter the equilibrium rates in the dark without any chemical action, then it is safe to say that forces within the atoms themselves can maintain different permanent equilibrium rates. These conclusions are far reaching and will be discussed after more careful investigations.

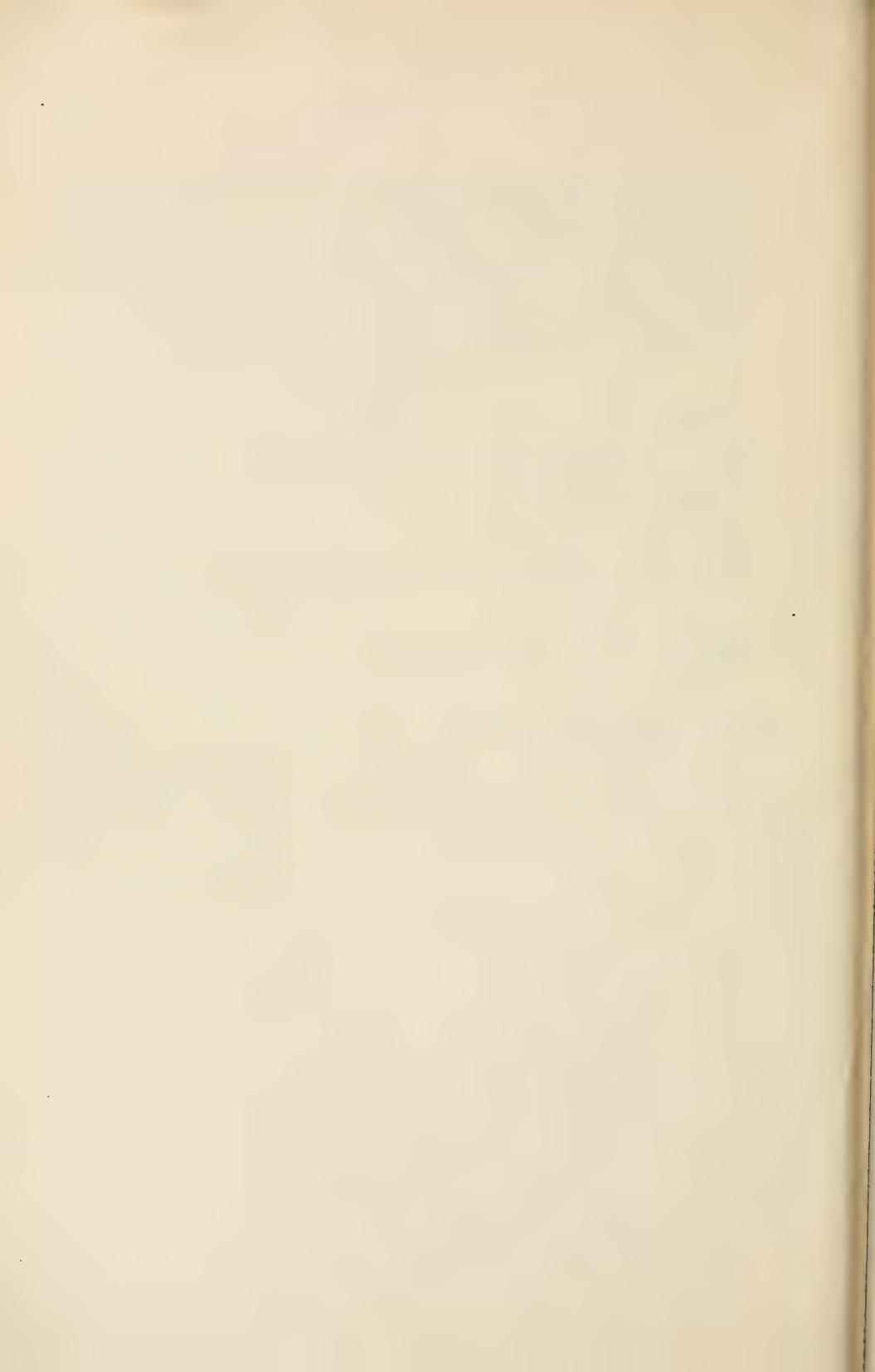
SUMMARY.

1. The effective depth of penetration of the selenium in the Giltay cell by light is about one eighth of the thickness of the selenium.
2. The entire amount of the selenium on the Giltay cell is conducting and light-sensitive.
3. Therefore the effective depth of penetration is about 0.014 mm.
4. The effective depth may be very much greater than the greatest depth reached by the light.
5. The effect of filing or sand blasting the selenium surface is to increase the conductivity. The nature of the action is important and should be investigated further.
6. Knowing the depth of penetration, we can now solve for new rates of change which will be slightly different from those recorded previously, and their significance should be more apparent.

I wish to thank Mr. Ernest Dieterich for so ably assisting me in much of the experimental work and for his kind interest in the problem.

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AN ELECTRICAL METHOD OF MEASURING SMALL INTERVALS OF TIME.

BY F. C. BROWN.

WHEN it is desired to measure the time between two mechanical operations, we have found that it may be carried out quite accurately by the use of resistances, battery, ballistic galvanometer, condenser, and contact keys. The principle is based on the relation between the electro-magnetic and the electro-static systems of units, and if we define the ohm in terms of the dimensions of a mercury column, the method is an absolute one. Aside from the advantage of having an absolute measure of time in terms of length, or of length, mass and resistance, the advantages of the method are simplicity and ease of manipulation. The interval of time to be measured may be diminished to the limits of dependable electrical contact, no doubt less than 0.001 second. How large the interval may be varies from 0.4 second to several seconds depending on the period of the galvanometer.

THEORY.

The theory of the method is essentially the same as that given in a previous paper on a method of measuring fluctuating resistances,¹ but as Dr. Erich Schneckenburg, of Berlin, has kindly pointed out that the method of derivation of equation (1) in that paper is not obvious, I shall briefly review the essential steps.

Suppose it is desired to know the interval of time, Δt , between the making of electrical contact at t_1 , and the time of breaking of contact at t_2 . It is to be shown that this time interval varies directly as the throw of a ballistic galvanometer which has been connected, as shown in Fig. 1, in a Wheatstone's bridge circuit during the interval.

Considering the battery resistance small compared to the other resistances, we obtain, by Kirkchhoff's and Ohm's Laws, the current through the galvanometer to be

$$i = \frac{E(aR - bx)}{(k_1x + k_2)^2}, \quad (1)$$

where

$$k_1 = Gb + aG + ab + aR + bR,$$

$$k_2 = aRG + bRG + abR.$$

¹ By Brown and Clark, PHYS. REV., XXXIII., p. 53, 1911.

By differentiating equation (1) with regard to x , we have

$$\frac{di}{dx} = -\frac{E(bk_2 + k_1aR)}{(k_1x + k_2)^2}. \quad (2)$$

We may write this equation in the following form and keep within the accuracy of laboratory experimentation,

$$\Delta i = -\frac{E(bk_2 + k_1aR) \cdot \Delta x}{(k_1x + k_2)^2}, \quad (3)$$

where it is understood that if the value of Δx is relatively too large a small correction must be added.

Now if it is agreed that Δx is to be measured as the amount of variation of x from that value which gives no current through the galvanometer as required by equation (1), then obviously $\Delta i = i$, and since the negative sign is of no importance,

$$i = \frac{E(bk_2 + k_1aR) \cdot \Delta x}{(k_1x + k_2)^2}. \quad (4)$$

Since the quantity of electricity that passes through the galvanometer as the result of the closed circuit during the interval Δt is $Q = i \cdot \Delta t$, and since in a ballistic galvanometer $K \cdot d = i \cdot \Delta t$, where K is the usual constant as obtained by a standard condenser and a known electromotive force, it follows that,

$$\Delta t = \frac{K \cdot d \cdot (k_1x + k_2)^2}{\Delta x \cdot E \cdot (bk_2 + k_1aR)}. \quad (5)$$

The only qualification, that should be made to this result is, that either the galvanometer coil must not have moved over an appreciable distance during the time interval to be measured, or that the effective resistances in the closed circuit should be so large that the damping action can be neglected. I take it that it is quite generally understood that self induction in the coil of a ballistic galvanometer can be disregarded. At any rate the experimental results in this paper will obviously warrant the assumption.

If a standard condenser of capacity C is charged by the same electromotive-force E , and then discharged through the same galvanometer, thereby giving a deflection d' , we may write equation (5) in the form,

$$\Delta t = \frac{C \cdot d \cdot (k_1x + k_2)^2}{\Delta x \cdot d' \cdot (bk_2 + k_1aR)}. \quad (6)$$

We therefore have the interval of time between the two contacts

measured in terms of the units of length and the units of resistance, and if we choose to define the unit of resistance in terms of the dimensions and the mass of a mercury column, our fundamental system of units may be regarded as solely based on the units of length and of mass. The relative merits of the unit of time as a derived unit will be discussed later.

EXPERIMENTAL TEST.

In order that the method may be workable it is sufficient to show that the time interval, between contacts at t_1 and at t_2 , varies directly as the deflection of the galvanometer, and that the computed value of the interval agrees with that observed. In our former paper the relation between the deflection and the time was recorded, but the linear relation did not hold for greater values of the time than 0.2 second. The lack of agreement beyond this point has since been found to have arisen from inaccurate theoretical calibration of the timing pendulum, and not to the fact that the galvanometer coil was not in its zero position while the entire quantity of electricity was impressed, as was previously supposed. Using correct values of the time as obtained by an experimental calibration of the pendulum, Messrs. T. Ingwaldson and J. S. Hilliard of our laboratory have obtained the observations shown on the curve in Fig. 2. Each point shown on the curve is the average of four observations. The accompanying table gives a fair representation of the reliability of the observations for a single setting of the keys. However it was found at the close of the observations that there was an error of about one mm. in the throw of the galvanometer due to the inaccurate setting of the keys.

TABLE I.

Time Interval Between Keys. Seconds.	Throw of Galvanometer. Mm.
0.009.....	6.0; 5.8; 5.5; 5.7.
0.045.....	26.5; 26.8; 26.8; 26.8.
0.38.....	222.0; 222.0; 221.8; 222.4.
0.09.....	53.0; 53.0; 54.0; 53.5.

The indicated values of the resistances used for balancing the bridge were, $a = b = x = 9,000$ ohms, and $R = 9,004.6$ ohms. The source of electromotive force was a storage battery of 38.0 volts. The value of R indicates the probable error in the resistances. In order to obtain the observations given above the value of x was changed to 9,100, thereby giving a value of $\Delta x = 100$ ohms. The resistance of the galvanometer was 950 ohms, and its period was 26.7 seconds.

The linear relation between the throw of the galvanometer and the time holds between 0.002 second and 0.32 second as accurately as the

particular apparatus was capable of testing. Of course for longer periods of time there would appear appreciable errors due to the swinging of the galvanometer coil in a closed circuit of high resistance. It is possible to correct for this error or to diminish it greatly by increasing the resistances and by increasing the period of the galvanometer. By increasing the mass of the galvanometer coil without increasing its inductance, *i. e.*, such as is done by adding weights to the coil, will clearly doubly lessen the relative error due to the cause above mentioned. But as adding mass in this way also decreases the sensibility, I am not prepared to say how far the last idea could be carried satisfactorily. To show the adaptability of the method for measuring intervals of time larger than those given in Table I., the period of the galvanometer coil was increased to 91 sec. by using a phosphor bronze strip suspension 1 meter in length.

TABLE II.

Deflections.

1 Period.	Current Direct.	Reversed.	
0.9 second.....	33.6 34.0 32.0 zero at 3.5 34.2 32.8	28.0 26.0 27.8 26.0 26.2	av. 30.1
2 periods.....	56.5 57.0 55.8 zero at 5.0 55.0 55.4	65.5 64.5 64.1 64.1 66.1	av. 60.5
3 periods.....	94.5 87.2 87.8 zero at 3.0 90.0 86.0	92.3 94.0 93.1 92.0 92.5	av. 90.7
4 periods.....	109.2 108.0 110.5 zero at 4.0 110.2 110.5	116.0 118.2 117.0 117.5 118.4	av. 113.7
5 periods.....	139.0 139.2 139.2 138.9 138.5	131.0 130.1 129.5 129.3 131.2	av. 134.6

The time interval was measured in terms of the number of swings of the pendulum. The keys were knocked down always at the middle of the arc. The period was about 0.9 second and the intervals were therefore some multiple of 0.9 sec. The observations are shown in Table II. The resistances used for balance in the bridge were 9,000 ohms each, and Δx was 500 ohms. A single dry cell was in circuit. When the galvanometer period is so large it is highly advisable to determine the zero position from the amplitude readings to the right and left such as is practiced in balance work. After the zero position is found it is very easy to bring the coil to rest.

It is observed that up to 3 periods, *i. e.*, 2.7 seconds, the deflection is proportional to the time interval, but beyond this the deflection falls off quite rapidly.

However by replacing the 9,000 ohm resistances in *a* and *b* (see Fig. 1) with 100,000 ohm values each, the deflection was proportional to the time up to about 3.6 seconds as shown in the following table, where each recorded value is the average of ten observations.

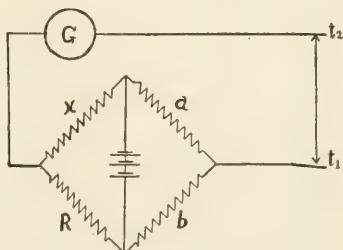


Fig. 1.

TABLE III.

2 periods.....	55.0
4 periods.....	110.7
5 periods.....	132.6

The foregoing results would seem to indicate that for large intervals of time it is more important to have a long period than it is to have extremely high resistances.

In order to test the adaptability of the method for absolute determinations of time, the constant of the galvanometer as obtained by equation (5) was compared with the value as obtained by the well-known battery and condenser method. By the current method the value was calculated to be $K = 1.77 \times 10^{-10}$ coulombs per mm. and by the second method, $K = 1.82 \times 10^{-10}$. This variation is quite within the limits of error of the capacity and the resistances used. As we did not have a standard condenser or resistances of the highest accuracy, it was not considered worth while to investigate the possible accuracy of the method any further.

As a practical laboratory method of measuring small intervals of time I believe that the scheme presented should be useful in certain kinds of

work, wherever it is feasible to mark time by electrical contacts. We believe that it is advisable to reserve in every laboratory a ballistic galvanometer of very slow period primarily for measuring time intervals. By posting at this galvanometer particular values of resistance and of

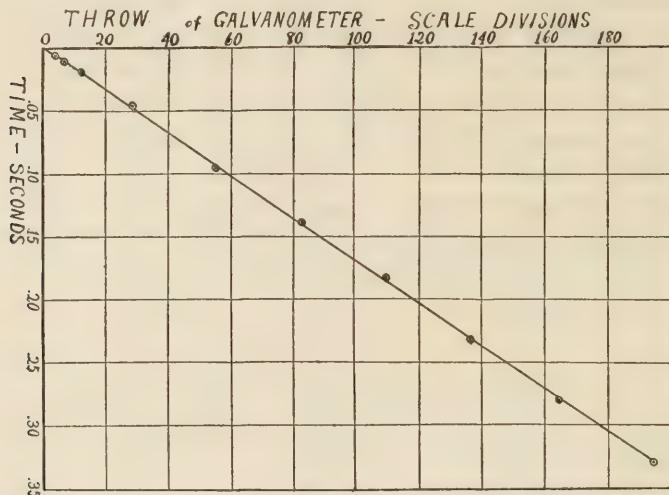


Fig. 2.

electromotive force to be used, and also the equivalent time interval, as calculated, for one division deflection, the troubles of calculations can be eliminated once for all. By taking only the most elementary precautions therefore the method should in many cases supplant a chronograph and standard clock. From this point of view the simplicity and quickness of manipulation are striking.

If it is desired to measure two or more time intervals simultaneously, several galvanometers and sets of keys may be connected in the same bridge circuit. The use of two galvanometers is illustrated, as used for measuring fluctuating resistances, in my previous paper on the recovery of the Giltay selenium cell and the nature of light-action in selenium.¹ If one observer wishes to read several time intervals simultaneously, he can do so by altering the periods of the galvanometers sufficiently so that he can have time to record each deflection.

THE ADVISABILITY OF THE SECOND AS A DERIVED UNIT.

Quite apart from the usefulness in the laboratory, are the considerations concerning the practicability of the method for determining the absolute unit of time. In this discussion any of the well-known methods used

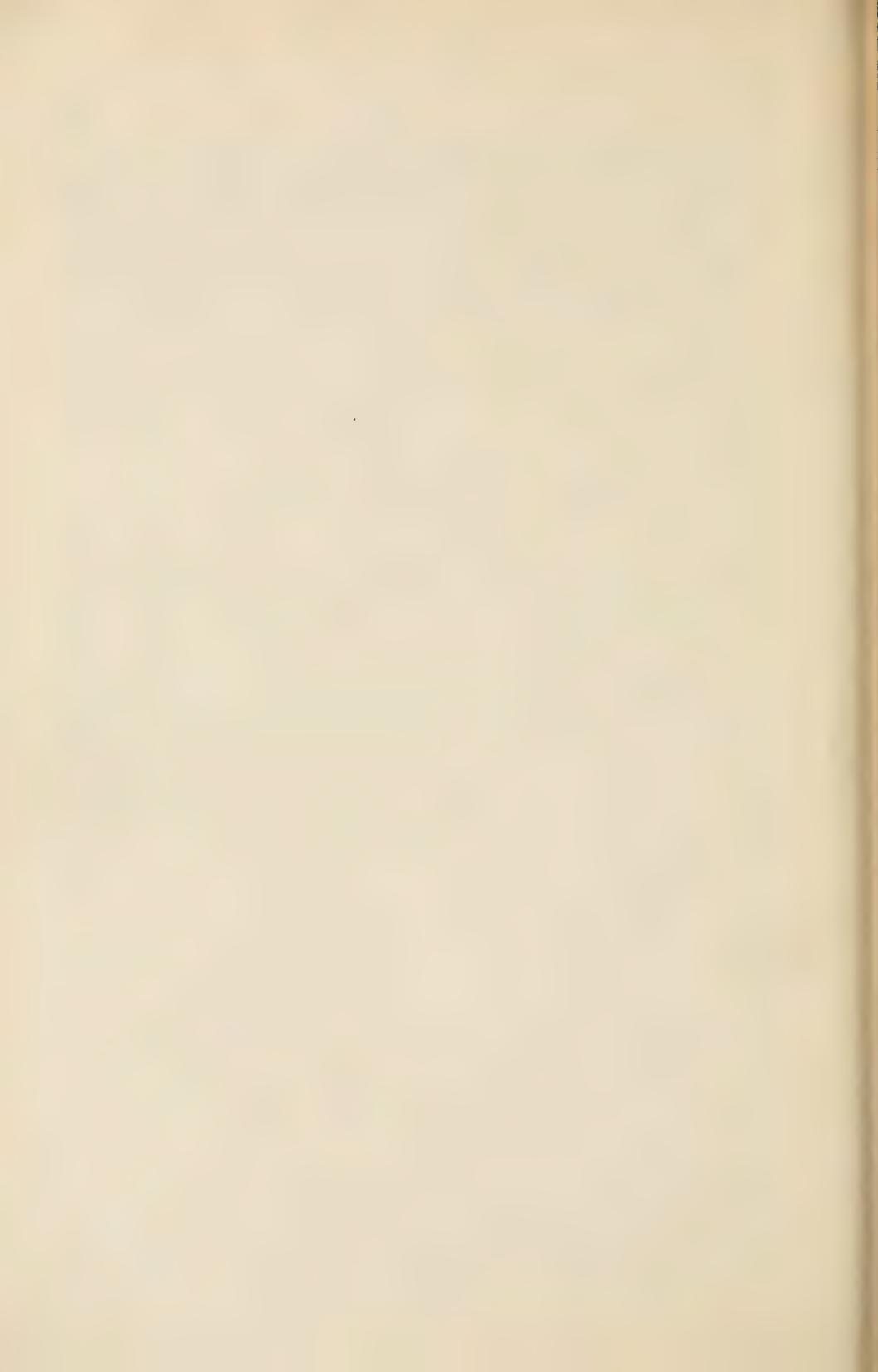
¹ PHYS. REV., XXXIII., p. 412, 1911.

by standard laboratories might be substituted. The only question is whether it is best to have the second as a fundamental or a derived unit of time. A fundamental absolute unit should have two distinct merits. It should be one capable of being reproduced to a sufficiently high degree of accuracy, and it should be unvarying for all time. As is well known our present fundamental absolute unit of time fulfills the first requirement remarkably well, but there is considerable doubt as to how long it will remain fixed. Tidal action, the shrinkage of the earth, friction with meteorites and friction of the atmosphere with itself, in addition to friction of possible electromagnetic origin, all tend not only to vary the value of the second, but also to make it almost a hopeless task to satisfactorily correct the unit for future periods of time.

By way of comparison, there is no question but that we cannot reproduce the unit of resistance, and consequently the derived unit of time, with as great accuracy as we can reproduce the present absolute fundamental unit of time, but on the other hand we have no information that would lead us to believe that the unit of resistance, defined in terms of the dimensions and mass of a mercury column, would not remain fixed.

It seems wise to suggest therefore that it would be worth considering the advisability of adopting our present unit as a secondary standard, which might be rechecked and revised in the distant future, if the electrical method, with the ohm as the fundamental unit, should show the value of the second to be materially in error. At any rate the temporary establishment of the unit of time defined from as many sources as possible might lead to discoveries of far-reaching importance.

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NOTES ON THE ELASTIC PECULIARITIES OF PLATINUM-IRIDIUM WIRES.

By L. P. SIEG.

1. *Introduction.*—The interesting elastic properties of platinum wires alloyed with iridium have been discussed in several papers.¹ The hope has been expressed at several times during the work of determining the equations that would represent the elastic action of these wires. The only matter that seemed to stand in the way of one's obtaining such definite mathematical relations was the lack of a sufficient variety of data. During the past two years many additional observations have been made on these wires, but in spite of the additional information gained by these experiments, no successful mathematical theory has been reached. However, it was thought best to present some of the more interesting elastic peculiarities of these alloys. Many of these results are very suggestive in the general subject of elasticity.

2. *Test of Hooke's Law.*—For many of the phenomena connected with these wires the former papers should be consulted. Only one result will be repeated here, as it is of importance in this section of the work. The wires which are used as the suspensions for torsion pendulums are alloys of platinum with various percentages of iridium. Most of the results are on a forty per cent. alloy, and it will be understood that this particular alloy is meant unless the contrary is stated.

The pendulum is twisted from the zero position to an amplitude of about 12° per cm. of length, and its period is determined as a function of its amplitude.² In Fig. 1 is shown a curve representing a typical results of such an experiment. For the special methods of observation, timing,

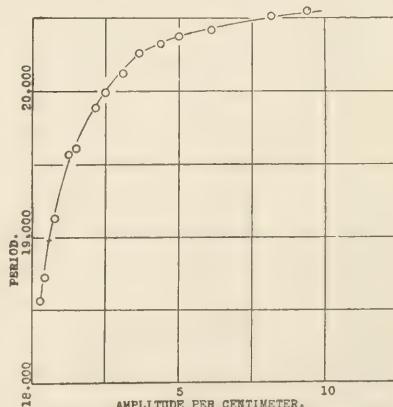


Fig. 1.

¹ For references to former papers see PHYS. REV., XXXI., 1910, p. 421.

² In former papers the word "amplitude" was used to represent the complete range of vibration. In the present paper it is used in its ordinary sense as referring to the angular displacement from the center.

etc., the former papers should be consulted. One of the first thoughts that occur to one in observing this curve is that perhaps here is a case where Hooke's law does not hold. The large period which stays almost constant down to an amplitude of about 5° per cm. of length seems to correspond to a constant and small restoring torque in the wire. Down to this place on the curve the conditions seem to be nearly normal. However, below this amplitude the period falls off rapidly, indicating thereby the possibility of an increase in the restoring couple per degree of twist. Some experiments were made to test this point. In the experiments recorded in some of the former papers¹ static determinations had verified the fact that Hooke's Law holds almost exactly up to the maximum twist. So from static determinations there is no evidence of any change in

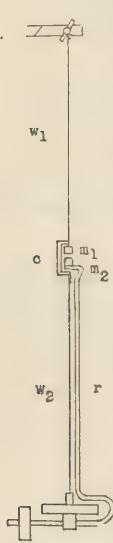


Fig. 2. m_1 is represented by x_1 , and of that from m_2 by y_1 . Suppose now the system is twisted. Let the new reading of the spot from m_1 be x_2 , and from m_2 be y_2 .

The twist of the wire w_1 is represented by $x_2 - x_1$ while the twist of w_2 is represented by $(y_2 - y_1) - (x_2 - x_1)$. With this apparatus we are prepared to test Hooke's Law both statically and kinetically, provided we assume that the above law holds for the steel wire. This latter assumption seems reasonably justified, at least within the experimental possibilities of this apparatus. For static determinations the lower weight was twisted, after the zero positions of m_1 and m_2 had been determined, was clamped at various degrees of twist, and the several corresponding readings of m_1 and m_2 were determined. In the kinetic observations there were two plans used. In the first place

¹ Loc. cit.

the system was vibrated and the simultaneous turning points of the spots of light from m_1 and m_2 were noted by two observers. These observations gave information of course at the turning points only, and in a way this experiment is not essentially different from the former static ones, for the wires were at the moments of observation, momentarily at rest. In order to test the action during the actual vibration of the wire, recourse was had to photography. The camera was focused on a portion of the scale where previous observation had located the simultaneous appearance of the two spots of light. The rest points of m_1 and m_2 were of course first determined, then during the actual vibration an instantaneous exposure of the two spots of light was made. Exposures were taken at several different parts of the scale, corresponding to various degrees of twist, and of parts of the vibration. The results of these observations, which to save space are not presented here, indicate clearly that within the accuracy of the method used, the restoring torque is at all times, whether the wire is in motion or not, proportional to the angular twist. So one must look elsewhere than to the failure of Hooke's Law for the explanation of the curve in Fig. 1.

3. *Test for Angular Harmonic Motion.*—An indirect test of the question raised in section 2 above seemed possible. That is, if Hooke's Law fails, then perhaps the motion of the vibration is not angular harmonic. It seemed worth while then to test this point. At first an attempt was made to arrange below the wire under test a second torsion pendulum having a steel suspension. The plan was to use two mirrors, similar to the arrangement in Fig. 2; to adjust to equality the periods and amplitudes of the two pendulums, and then to set the two going simultaneously from the same point of rest. It was hoped that if the vibration of the platinum-iridium wire was not truly angular harmonic, that the two spots of light, while starting together, and reaching possibly the extreme amplitudes at the same time, would not at the other points of the scale be together. It was found impossible to adjust the two pendulums together, for while the steel one was practically isochronous, the other one, as indicated in Fig. 1, changed enormously in its period with varying amplitude. The method was then abandoned on account of the many practical difficulties encountered. The next method, and the one that seems to have been successful, was to get a trace of the vibration on photographic paper mounted on the revolving drum of a chronograph. As the width of the chronograph cylinder was only 25 cm. it was necessary to have a small vibration. This in no way caused any difficulty, for the length of the wire was reduced to such an extent that the same twist per unit length as in former experiments was possible, even with the very

limited amplitude. A vertical slit of light was focused on the drum of the chronograph in front of which was a thin horizontal slit. This gave on the drum a very fine point of light, and this arrangement had the additional advantage over the focusing of a point of light in that small vertical oscillations of the vibrating pendulum were not recorded. Thus a perfectly smooth curve was obtained. The room was darkened, the drum covered with the photographic paper, and the pendulum and the drum were started. When all was steady a cardboard stop was removed from the front of the horizontal slit, and light was admitted until about fifteen or twenty semi-vibrations had taken place. The paper was developed, and when carefully dried was ready for measurements. The paper was of an excellent heavy stock and if there was any shrinking it was thought that it would not affect any one measurement more than any others. Several such records were obtained. Now before final measurements on these curves can be made, two reductions must be carried out. The first is the reduction of the tangent of the angle of twist to the angle, for the drum was tangent to the circular scale. The next reduction was a little more difficult to make, and also a little more uncertain. Those who have read the former papers will recall that the logarithmic decrement of the vibration of these wires is not only variable, but is also very large. So the traces on the photographic paper were similar to such a highly damped vibration as that represented in Fig. 3. This figure is, however,

much exaggerated. In the first place along the central line AB , each segment such as CD is divided into n equal divisions. In the present work n was made equal to ten. Ordinates were erected at each of these divisions. Let the ordinates erected at the middle points of the segments be represented in length by a_1 , a_2 , a_3 , etc. The times represented by the distances between these small divisions are each

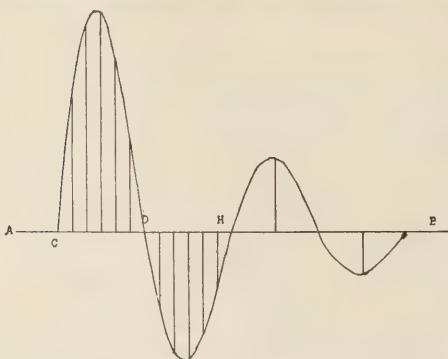


Fig. 3.

taken as unity. Then in Fig. 3, the times at which the amplitudes a_1 , a_2 , a_3 , etc., occur are 3, 9, 15, 21, etc., units. Then the amplitude of any of the median ordinates a_1 , a_2 , a_3 , etc., is supposed given by the expression

$$a_0 = a_1 e^{-mt},$$

where a_1 is any measured median ordinate, a_0 the first measured median

ordinate, t the time elapsed in the arbitrary units, while m in this wire is a variable function of the time elapsed, and not a constant as it is in most wires. The value of m as a function of the vibration number is plotted in Fig. 4. After m is determined, any other than a median ordinate is measured and reduced to what it would be were there no damping. To illustrate briefly the general method, a special case from Fig. 3 will be taken. Suppose we take the measurement of the ordinate at H . To get its adjusted length it is adjusted by multiplying by e^{11m} ; the number 11 representing the number of units of time elapsed since the beginning.

The value of m is taken from the curve in Fig. 4 at the time interval 11. This is found to be about .00410. After all these ordinates are measured and adjusted (and there were over ninety of them to each curve) to what would have been their magnitude had there been no damping, all the corresponding ordinates were averaged. Lastly these were compared with multiples of the natural sines of the corresponding angles. The constant multiplier of $\sin \theta$ was so taken that the values agreed at 90° and of course at 0. The results of a large series of such measurements and reductions are given below in Table I. It seems then as a reasonable result of these measurements and reductions, to assume that the vibrations of the torsion pendulum were angular harmonic. And this in turn gives us additional evidence of the validity here of Hooke's Law during the vibration.

TABLE I.

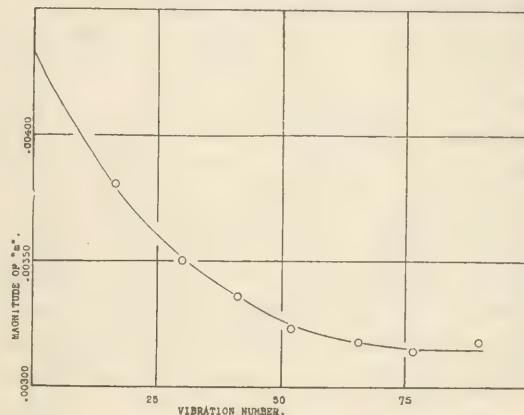


Fig. 4.

θ	Const. $\sin \theta$.	Means of the Adjusted Ordinates.
0	0	0
15	3.32	3.29 \pm .01
30	6.41	6.39 \pm .02
45	9.06	9.03 \pm .02
60	11.09	11.08 \pm .02
75	12.37	12.35 \pm .01
90	12.81	12.81 \pm .01

It might be mentioned incidentally under this section that from the photographic records there was an opportunity of measuring the period, and amplitude of course, of the vibrating pendulum. These measurements give results identical with those obtained with the method of observation used in the preceding work, and so give one the assurance that the methods there used were sound.

4. *Effect of Long Continued Rest.*—The relation between amplitude and period in these pendulums is not by any means a constant one, as reference to former papers will make plain. Briefly, if the wire has been annealed at red heat, and then vibrated through not more than one or two degrees per cm. of length, its period is low and nearly constant over this range of vibration. However, if the same pendulum is vibrated or even twisted through ten or twelve degrees per unit length, and then vibrated through the same range as before, its period is found to be not only much larger but also to change much more rapidly with amplitude. These two points are shown in curves (e) and (a) respectively of Fig. 5.

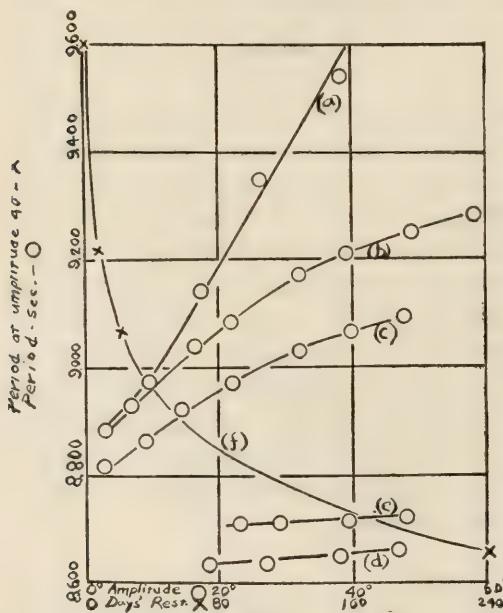


Fig. 5.

In all the experimental work the general method of wiping out the history of the wire was to anneal it under load at red heat. In every case this gave the wire the smallest period. By chance the wire had been left hanging for several months without having been annealed before this long period of rest. On vibrating the wire at the end of this period I was surprised to find from the relation between amplitude and period that the effect of the long rest had been not only similar to the effect of annealing, but that it had actually carried the wire beyond this point. Here was

a case where the wire, as it were, automatically annealed itself. The results of this experiment are shown in curve (d), Fig. 5. To make certain of the matter, the wire was annealed and the old position of the curve for period and amplitude was obtained (curve (e)). Of course this suggested that there was a kind of recovery in the elastic condition

of the wire and to gain information on this point, observations were made after 22 hours' rest (curve (b)), and after 25 days' rest (curve (c)). The original observation had been made after 240 days' rest. In curve (f) of Fig. 5 is represented the relation between the period at a double amplitude of 40° and the number of days that the wire has rested. A general logarithmic recovery curve is clearly indicated.

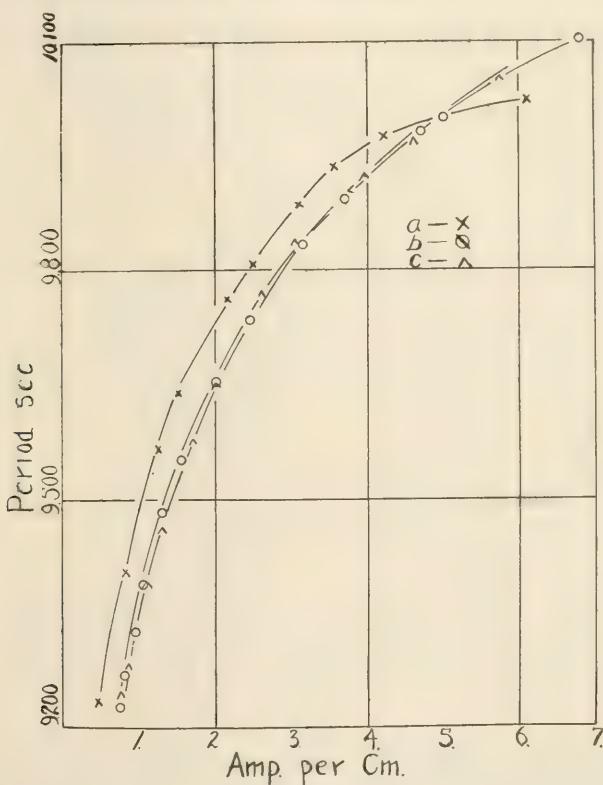


Fig. 6.

5. *Effect of Variation of Length of Wire, and Speed of Vibration.*—In a former paper¹ there were recorded results wherein it appeared to be indicated that even with a careful preliminary treatment of the wire there were differently shaped curves connecting period and amplitude for different periods of vibration. A valid objection to this former work would be that the air friction in the different cases would be so different with different velocities of vibration that the results for internal friction could not well be compared. In view of this a set of observations was made in which external friction was made practically constant. Whether

¹ PHYS. REV., XXXI., 1910, p. 449.

we assume the air friction to be dependent on the first, second, or other power of the velocity of vibration, the air resistance for varying lengths of the wire can be made the same by adjusting the periods so that they are proportional to the maximum amplitude of vibration. Since in the various cases the maximum amplitude of vibration is made proportional to the length of the wire, the period then, simply, is made proportional to the length. This was accomplished without changing the load on the wire, by sliding to or from the center two brass cylinders which fitted over a horizontal steel rod. The results are best explained from the three curves of Fig. 6. These curves are all reduced to the same scale

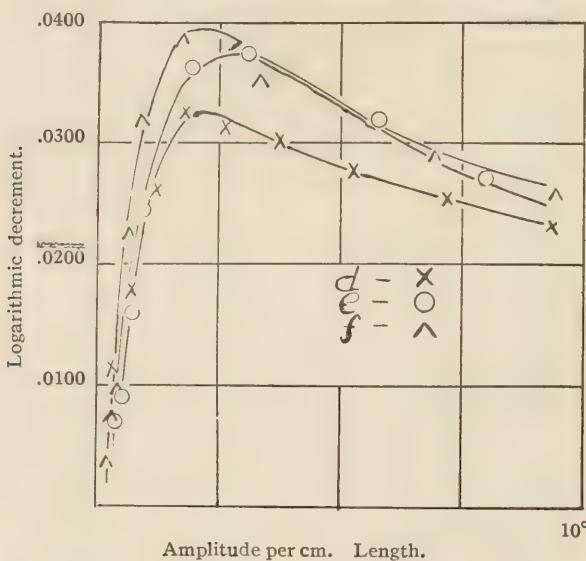


Fig. 7.

so that they can be compared. Curve (a) represents the longest wire, and the longest period of vibration; curve (b) represents the medium, and curve (c) the shortest wire and the shortest period of vibration. The effect noticed in the previous work is here verified. The faster the vibration the sooner the curve connecting period and amplitude turns down toward the X-axis. Of just what significance this is, is at present not clear.

In the above experiments with constant load, with constant initial twist per cm. of length, but with variable length of wire it is interesting to note the variation of the logarithmic decrement with the mean amplitude of vibration in the three cases considered above. These variations are shown in Fig. 7, where curves (d), (e), and (f) refer respectively to the conditions represented by curves (a), (b), and (c) of Fig. 6. Here

again is to be noted a progressive change wherein the shortest wire—likewise the one having the smallest period—has the largest decrement for a given amplitude. The peculiar shape of the logarithmic decrement amplitude curves has been previously noted.¹ It is to be observed that at a twist of from two to three degrees per unit length there is a sudden break, not only in the logarithmic decrement-amplitude curves, but also in the period-amplitude curves, as can be seen in Figs. 7 and 6 respectively.

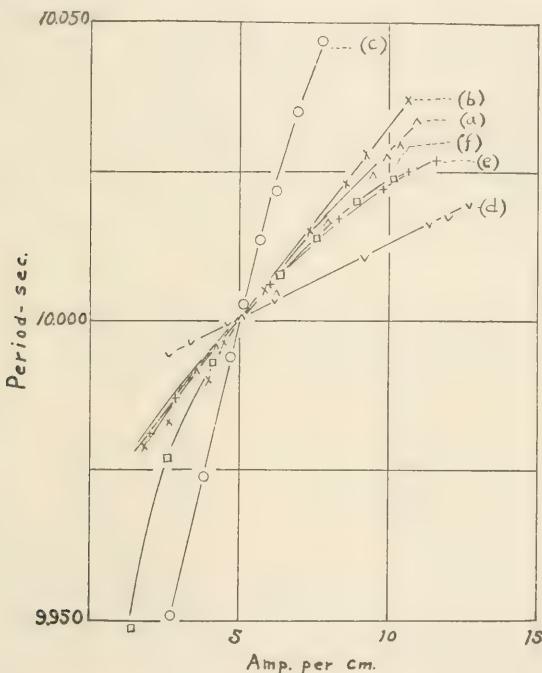


Fig. 8.

6. *Effect of Drawing.*—It was found practically impossible to draw the 40 per cent. wires with any plate we possessed, on account of the extreme brittleness of the wires. Even annealing at red heat had but small beneficial effect. Only with a very gradually graded draw plate could one have much hope of success in drawing down these wires. However, a wire of smaller percentage of iridium, probably 25 per cent., proved to be more easily drawn. The exact composition of this wire is not known. The following procedure was adopted. The wire was annealed and drawn down one size. A piece about 10 cm. long was cut from this, and the remaining part of the wire was again annealed and drawn through the next smaller hole. This was continued until three specimens, represent-

¹ Loc. cit.

ing three successive drawings were at hand. Each specimen was unannealed, but had been annealed just before its drawing. The only difference to be expected from these was that perhaps as the specimens grew smaller there would be a greater fraction of the wire affected by the drawing process. This is of significance in view of the following results. Two sets of experiments were performed. In the first one the three wires were used just as they came from the draw plate, and were vibrated under constant load, nearly constant length, constant initial twist per unit length, and with practically constant period. This latter was accomplished by varying the moment of inertia of the suspended system without changing its mass. In the second set of experiments the wires were first annealed at red heat and subsequently experimented on as in the first set. The results are most easily discussed from the curves of Fig. 8, and from the data in Table II. In Fig. 8 are platted the periods with amplitudes

TABLE II.

No. of Drawing.	Diameter of Wire (mm.).	No. of Vibrations from 12.5° to 4° .	State of Wire.
1	.181	170	unannealed
2	.163	158	unannealed
3	.151	66	unannealed
1	.181	280	annealed
2	.163	170	annealed
3	.151	104	annealed

for these wires. Curves (a), (b), and (c) represent respectively the conditions from the first, second, and third drawings of the wires in their freshly drawn condition, and curves (d), (e), and (f) represent the same wires after having been annealed. Two things will be observed. First the annealing acts to lower the period of a drawn wire just as it does to lower the period of a wire that has been vibrated for some time. Hence drawing and long-continued vibrations have similar effects on the wires. Secondly the effect of drawing becomes more and more pronounced the finer the wires become. This might be expected, for in the smaller wires the ratio of the surface to the volume becomes greater, in fact inversely as the radius, and the drawing apparently has most effect on the surface. In curve (c) we have a curve that is almost as pronounced as a similar curve for a 40 per cent. wire. It is evident then that to the quantities to which heretofore have been attributed the relation between period and amplitude, *i. e.*, to the per cent. of iridium, and the previous vibrational history of the wires, must be added the matter of the method used in the drawing of the wires. It will be noticed lastly that not even

an annealing at red heat is able to restore any of the drawn wires to the condition of the wire just larger than itself. Apparently the crystal structure has been so altered by the drawing that heating will not restore it. Probably long-continued rest under load, as described in section 4 of this paper, would restore all the wires to the same condition.

The effect of the drawing and the annealing is strikingly shown in another manner in Table II. In the third column is given the number of vibrations executed by the pendulum in dying down from an amplitude of $12^{\circ}.5$ per cm. to an amplitude of 4° per cm. The two effects mentioned in the above paragraph are here again clearly evident. In each case the annealed wire executes more vibrations over a given range of amplitude than the corresponding unannealed wire, and secondly the finer the wire in each set, the fewer vibrations there are in dying down over the amplitude range. It is certainly striking to have a wire whose cross-section is only two thirds of that of another wire of the same composition, die down in 66 vibrations, while the coarser wire continues to vibrate 170 times over the same range.

7. *Summary.*—Further study has been made of the elastic nature of platinum wires alloyed with iridium. The following points have been made:

(a) In spite of the peculiar variation of period with amplitude, and of the enormous change in the decrement of these wires as they die down in their vibrations, Hooke's Law has been found to hold, not only statically, but also kinetically.

(b) The torsional vibration of these wires has been proved to be practically angular harmonic.

(c) The elastic properties are profoundly modified by long-continued rest under load.

(d) With due allowance for the effects of ordinary external and internal friction, there is found to be a variation in the elastic properties of the wires with the speed of vibration, or at any rate with the period of vibration.

(e) The elastic properties are much modified by drawing the wires.

8. *Conclusion.*—It seems quite definite that all the observed phenomena connected with these alloys must be related to crystalline structure. Several attempts have been made to etch and examine cross-sections of these wires, but thus far no satisfactory specimens have been prepared. If we accept this hypothesis, then it is interesting to note how not only annealing and drawing can change the crystalline structure, but likewise strenuous vibration, and also long-continued rest. It is fortunate that common wires of pure metals and of alloys are not so sensitive to treat-

ment as are these. If they were, we should need in our laboratories the services of an expert historian, if we should ever expect to use the wires in exact measurements. That these effects are present in almost all wires, of course to a much smaller extent than in these platinum-iridium wires, is the belief of the writer, and further with these sensitive wires as exploring agents, we may hope to learn more concerning other elastic substances.

STATE UNIVERSITY OF IOWA,

July 22, 1912.

THE EARLY HISTORY OF INSTRUCTION IN PHYSICS AT THE UNIVERSITY OF IOWA*

BY C. R. AUBNER

On July 16, 1855, the sum of five hundred dollars was appropriated by the Board of Trustees of the State University of Iowa to equip the laboratories in chemistry and physics, which were to open for the first time in the following September. While united during the first months of the first year, it is clear that the chairs of chemistry and physics became distinct in January, 1856, when a "Professor of Natural Philosophy" was admitted to the faculty.

The course of study in physics included the unusual elementary subjects; the apparatus provided was described as follows: "A valuable suit of apparatus has already been secured for the use of this Department, of which the following are a few specimens: an Air Pump, at a cost of \$80; an Electrical Machine, at a cost of \$70; a Microscope, at a cost of \$65; a set of Mechanical Powers and Atwood's Machine, \$75." To this "suit" it was announced that additions would be made during the year. It was particularly mentioned that in the course of instruction the application of each subject to the "useful arts" was to be "carefully unfolded."

The reasons for the adoption of the lecture plan of instruction in 1856 were stated to be: first, that it might be possible to secure able professors in each department, since it was considered that no others could "possibly sustain themselves;" second, it would secure "a teaching more in accordance with the actual state and condition of science, which is, and must ever be, progressive;" third, it would enable the teacher to adapt his instruction to the capacity of the student and by this means secure his effectual progress; fourth, it would bring the "*living mind* in direct contact with *that of the student*" and thus awaken his powers, and "kindle his enthusiasm" resulting in a "higher and more perfect culture;" and finally, it was the "only method followed in the Universities on the Continent of Europe," where the method had proved effective. The experi-

*The materials for this paper are taken from an unpublished history of the department of physics prepared by the writer for The State Historical Society of Iowa.

mental work was limited, therefore, to the lecturer; and actual laboratory manipulation was in no sense contemplated.

In 1857 a manifestly liberal view of the requirements of science was taken when \$500 was appropriated for chemistry, and \$100 for physics—all of which was to be expended under the direction of the President of the Board of Trustees, the President of the University, and the faculty acting jointly. This would insure, it seemed, a careful and wise expenditure, since all were supposed to be equally qualified to select apparatus that would meet the needs of a specialist.

Another suggestion of the absolute equality of subjects in the curriculum of that early day is seen in the reorganization of the University faculty in 1860. The Rev. James Lillie, M. D., D. D., had been selected as the head of the fifth department (that of physics and chemistry) and the Rev. O. M. Spencer had been appointed head of the third department (that of ancient and modern languages). But before actual work began these two gentlemen mutually agreed to exchange chairs.

Laboratory work by students in classes is said to have begun at the University, at least in a preliminary way, in 1869, which was in fact, the same year that the laboratory method was introduced at the Boston Institute of Technology. Indeed, it is claimed that the work at Iowa was carried out in greater detail than in the Boston Institute. The work at the University of Iowa during the next year included not only the usual lectures but also "practice in the laboratory," which was "obligatory and free of charge" during the first two years commencing with the sub-freshman year. The elements of physical science required five hours of laboratory practice each week. Certain courses including the hours mentioned were expected from all students in the University. All lectures in the regular work were to be followed by "laboratory practice" on the matter presented. For such purposes the large classes were organized in divisions under the personal direction of the head of the department, Dr. Gustavus D. Hinrichs, or his assistants. An official committee, reporting in 1872, said: "In several instances we observed entire classes engaged in illustrating their studies, preparing their own experiments, and recording the results as subjects for future recitations."

A journal by the name of *The American Scientific Monthly*, was

begun at the University in July, 1870. Popular science, with special reference to the daily increasing practical and social influence of science, science for schools, that is the lower schools, not only in general but also in suggesting apparatus and methods adapted to such instruction, were some of the definite objects to be advocated by this journal. Original contributions would be accepted and were to form a part of each issue.

The School Laboratory of Physical Science, a quarterly journal, succeeded *The American Scientific Monthly* in 1871. It had for its definite purpose the advancement of science in the common and higher schools. The first number, indeed, expressed the hope that a good school laboratory where "twenty-five pupils can experiment at the same time" would soon be found in every town of a thousand inhabitants.

Through the pages of this journal it is learned that "more than two hundred students" had experimented in the University laboratory from September to March, 1870-1871. Hinrich's *Elements of Physics Demonstrated by the Student's Own Experiments* was the complete title of the text used in the course of instruction. A journalist of this State, who visited the University laboratory at this time, wrote: "A marvel of studious industry is there. Young men and women, boys and girls, measuring, weighing, testing, demonstrating, and recording fact upon fact, that, at least in our school days, were pored over in a maze of bewilderment in dryest of text books to be bolted in sections without question."

That the work in physical science in the State University of Iowa was known not only at home but still better abroad, is well evidenced from editorials and contributions in the London journal, *Nature*. Referring to the laboratory work in Iowa the editor said: "We trust that these important reforms in science teaching will prove contagious and spread rapidly from the plateau of Iowa City to a region of even greater extent than the American continent." To the editor of *Nature* it was "deplorable to think how few school laboratories there are in England which could in any way vie with that of the Iowa State University."

Although the actual influence of this laboratory upon other institutions, not only below it but also upon those of equal rank, may not be measured, it is, however, reasonable to conclude that through the journals, text books, and reports, or other agencies of informa-

tion, many were led to consider the plan of introducing individual laboratory work early and extensively in the course. Indeed, Professor Hinrichs said that he had been for years "devising plans and means to enable schools of lower grade to introduce this system of instruction." It was natural then for students who had been under his immediate direction at once to put into execution such instruction. Instances to illustrate this are at hand.

In 1873 more than one hundred of the "journals of experiments" kept by students were carried to the Vienna Exposition in order to illustrate the work of this laboratory. *Nature*, in its commendation of Hinrichs's *Elements of Physics* considered the "journal of experiments as perhaps the most suggestive" part of the work. On the whole it was thought a "bold undertaking" to bring out such an "almost unique specimen of a practical treatise." The book was recommended for use in the schools of England.

Early in the development of the University laboratory, in physics, instruments were requested for the purpose of obtaining "authentic and complete records of the atmospheric phenomena for this region of the State." While the equipment was a part of the physical apparatus it was put to practical account in the establishment of the weather service for the State in 1875. Organized by Professor Hinrichs upon his own initiative and responsibility, the State was districted and hundreds of volunteer observers appointed to report to the central office in Iowa City. Five years of continuous service secured to these volunteers their instruments; and they were also granted a diploma by the director. Although none of these observers were paid anything, it is said that scarcely one withdrew during twelve years. The State contributed nothing to the undertaking—not even the expenses—until 1878.

From the above facts, and other related information, one may conclude that some forty years ago the foundations of a great scientific school were laid at the State University of Iowa. Its beginnings were known and appreciated in distant lands better than at home for the reason that the awakening relative to science in general began in European institutions. Why the development so auspiciously begun in Iowa was apparently suddenly halted, it is not easy to explain. One may suggest that the chief reason lay in the fact that the schools had hardly emerged from a period when there was but little science taught. Time enough had not

elapsed to permit the classics and the sciences to become mutually co-operative. The physics department of the University was in advance of its relative place in its environment, and a feeling antagonistic to it was in evidence. Nevertheless it had a large following among students from the very beginning. Again there appears to have been an overpowering opposition to a movement that would popularize learning which was not in accordance with ancient tradition.

Opposed to any reaction in such instruction and demanding more and more of its applied phases was the environment of this institution. The demand of this State, expressed in the strong words of governors and other public men, was for instruction that would serve an agricultural community. In spite of opposition to such growth within the institution itself development was inevitable. There is room for all in the University—but it has taken a half century to bring harmony.

THE NEW PHYSICS BUILDING AT THE UNIVERSITY OF IOWA

BY G. W. STEWART

Each new laboratory constructed for the study of physics represents an effort to respond to the demands of the physics of to-day, and to prepare for the demands of the physics of the future. Such a structure must be complete in all its appointments, and yet there must be a reasonable degree of flexibility in order to meet future needs. New laboratories of physics are therefore studies. It is from this point of view that a description of the laboratory at the University of Iowa is presented.*

The shape of the building is rectangular, this being determined by its location. As shown in the accompanying cut, the architecture of the building is somewhat unusual. Its design is that of the Italian Renaissance period with considerable Greek feeling in the details. It stands on the brow of a hill overlooking the Iowa River. Its exterior is in harmony with the Hall of Liberal Arts, the Hall of Natural Science, and the Old Capitol Building, all of which belong to the same group. The building is a very successful achievement in architecture, as it combines to a high degree architectural beauty and general utility.

The extreme dimensions of the building are 232 feet and 73 feet 8 inches. The floor plans show that the sustaining walls have been reduced to a minimum and consist only of the exterior walls, the corridor walls, and two transverse walls. All of these are constructed of brick. The building is finished in Bedford limestone.

On the interior, partitions are constructed of hollow tile, and the floors of hollow tile and concrete with steel beams extending from corridor to exterior walls. The reduction of the sustaining walls to a minimum permitted the adoption of the "unit system." It is

*The cost of the building, exclusive of furniture and apparatus, was \$225,000.00. It was designed by Messrs Proudfoot, Bird, and Rawson, State Architects, with the co-operation of the Department of Physics of the University. Ground was broken in the spring of 1910. The structure was not completed until two years later. Messrs James Rowson & Company were the general contractors of the building. The heating, lighting, plumbing, ventilating, and electrical service were installed under the supervision of Mr. J. M. Fisk, Superintendent of Buildings of the University.

possible by means of the tile partitions to divide the building into rooms of approximately uniform size and shape, viz., 13 feet by 23 feet, and each one of these is a "unit". Each unit has its own heating, ventilation, and lighting. The possibility of making the sizes of the rooms any integral number of units merely by the insertion or removal of partitions is distinctly advantageous in a building constructed for the continually changing needs of physics.

General equipment.—Each unit is heated by steam radiation controlled by a thermostat. In the latter the expansion and contraction of vulcanized rubber operates the valve of the radiator through the medium of compressed air. In each unit there is a ventilating inlet and outlet. The scale of the accompanying floor plans does not permit these ducts to be shown in detail. The ventilation is obtained by two 10 H. P. motor driven fans. The air is tempered when entering the plenum chambers, the temperature being automatically controlled here as elsewhere.

The lighting of the building was designed by Professor A. H. Ford of the Department of Electrical Engineering. Each unit has two 100-watt tungsten ceiling lights with shades, and in addition a wall bracket and a wall socket. The shades were selected so that the illumination is approximately uniform throughout each unit, and has a value of $2\frac{1}{2}$ candle-feet.

The equipment of the laboratories is, in general, three-wire 220-volt A. C. two phases, three-wire 220-volt D. C., special circuits to the main switchboard, hot and cold water, gas, and compressed air. The air is obtained from a G. E. direct-connected automatic compressor, capacity 25 cu. ft. of free air per minute at 40 pounds (maximum pressure 90 pounds). Systems for vacuum, oxygen, and hydrogen were not installed. The arrangement of shafts in the building permits such installations at any time in practically any laboratory in the building. Two of these shafts are next the elevator, unit 7, and two are located at the ends of the building. The latter are connected with the former and with each other by a tunnel which runs longitudinally under the basement floor.

Research Laboratories.—Most of the research laboratories are located on the basement floor. Particular care has been taken to make the basement (on the lower side the floor is less than two feet below the grade line) dry, free from pipes, uniform in temperature, and as habitable as any other portion of the building. There are

no piers for stability. Both the exterior and corridor walls are as stable as a well constructed pier could be. Further, the cement and concrete floor is laid directly upon the ground. Supports of cement blocks have been built to suit the individual experiments and have been found to give great satisfaction inasmuch as they combine the stability of piers with the additional advantage of flexibility.

It will be noticed that the windows are recessed in these research rooms. The radiator, placed directly in front of the window, does not interfere with experimental work. In fact, a stable support extending entirely across the unit can be fastened to the outside wall.

The room marked "constant temperature" is really not different in construction from the other research laboratories, save that the exterior wall is entirely underground. It is reserved for such experiments as require a constant temperature housing. Such enclosures will be built to suit the experiments.

Undergraduate Laboratories.—One large laboratory is devoted to advanced instruction in all subjects excepting electricity. This and the electrical laboratory are located on the first floor. On the second floor are the elementary laboratories. In each laboratory is a general switchboard from which circuits are carried in conduits to various parts of the room. In the advanced laboratory are situated eight small dark rooms which are without doors and which have good ventilation. In the elementary laboratories darkened sections are secured along interior walls by using adjustable curtains.

Library.—The library is located at the most prominent point in the building. Its arrangement and its location make the library the real heart of the work in physics.

Lecture Rooms.—In order to secure permanently suitable quarters for the lecture rooms, it was necessary to go to the third floor. The requisites for lectures in physics seem to be a well-appointed, well-lighted and easily darkened lecture room, a preparation room, and a commodious apparatus room. Moreover it is necessary to have more than one lecture room. All these requirements have been met. The equipment of the future will doubtless demand more and more sets of apparatus arranged ready for use, and also larger individual pieces. Because of this anticipated increased demand a large apparatus room, 82 feet by 25 feet, was designed. The lecture rooms and the apparatus room are arranged *en suite*, and

carts on ball-bearing rubber tired castors make the transportation of apparatus a simple matter.

The risers for the tier of seats in the lecture rooms were determined graphically. In a cross section of the room, lines were drawn from a point one foot above the center of the lecture table to the tops of the heads of a supposed audience. The vertical angles so produced were made equal. This gives an advantage in one sense which is in proportion to the distance from the lecture table. The risers in the larger room are as follows, expressed in inches: 0.0, 4.3, 4.8, 5.5, 6.6, 7.6, 8.4, 9.3, 10.4, 11.1, 12.4.

The equipments of the two lecture rooms are similar. In the large room there are two switchboards located on the wall at the rear of the table, one next each door entering from the preparation room. One of the boards is used for the various lantern circuits terminating in various parts of the room, and the other is a switchboard from which eight independent circuits run to the lecture room table. At the latter board any electrical circuit from the table can be connected with the A. C., D. C., storage battery, and indeed any part of the laboratory. There are no rheostats on these switchboards.

The lecture table was kept as simple as possible. There are the usual conveniences of sinks, gas, and compressed air, and also additional pipes running to the shaft in that corner of the building. The proximity of this shaft means the possibility of bringing to the lecture table almost any kind of service desired in the future.

The skylight screens which darken the large lecture room are operated by pneumatic hoists, the pistons of which are connected directly to the screens. One hoist operates the screen over the lecture room table, the other screens are operated by a second hoist. The hoists are double acting, do not require automatic stops, are easy of manipulation, and seem to promise permanent satisfaction. The valves are controlled at the rear of the lecture table.

On this floor the windows are seven and one-half feet from the floor. The apparatus cases can therefore be placed without regard to the location of the windows.

Storage Battery.—The stationary storage battery consists of 40 40-ampere (normal) cells, and 80 10-ampere (normal) cells. These are placed in series, and wires from the junction points lead to a switchboard located near the battery. On this board are placed

the fuses, and from it run the circuits to the storage battery board in the general switch-board room. The voltage between any two of these circuits is determined by the grouping selected on the basement board.

The present grouping selected and repeated throughout the battery is 2, 4, 6 and 8 volts.

A number of portable cells, 5 and 1.5 amperes are used wherever they are advantageous.

Floors.—There seems to be a question as to the most desirable floors for a physical laboratory. The corridor floors in this building are terazzo. All the other floors are cement. The result is that the entire floor area is practically free from vibrations. In order to prevent the dust usually experienced with cement floors, two precautions were taken. First, care was taken to have the floors laid properly. This is more important than any subsequent treatment. After the floors had become perfectly dry, a sodium silicate treatment, highly recommended by Albert Moyer of the Vulcanite Portland Cement Company, was tried. Dilute solutions of four parts water to one of sodium silicate (40° Baume) were applied until the floor had absorbed a maximum. It is thought that the sodium silicate forms in the cement a silicate of lime which serves as a binder. Thus it is not a surface treatment. The experience of a few months indicates that the floors will be very satisfactory.

Shop.—In the instrument makers' shop each machine has its own motor drive. There are no overhead wires or shafting. The shop equipment, while not complete, may be of interest on account of its selection. The most important machines are a 14-inch Hendey engine lathe, an 8-inch Rivett precision lathe, a No. 1 Brown and Sharpe Universal Milling Machine, a 20-inch Mechanics drill press, a Hisey-Wolf sensitive drill press, a No. 2 Crescent Universal saw-table, and an Oliver 12-inch speed lathe. The room designated as a "General Shop" is intended in the main for students' use. It contains glass-blowing tables, several lathes, a drill press, a wood-working bench, and other shop equipment.

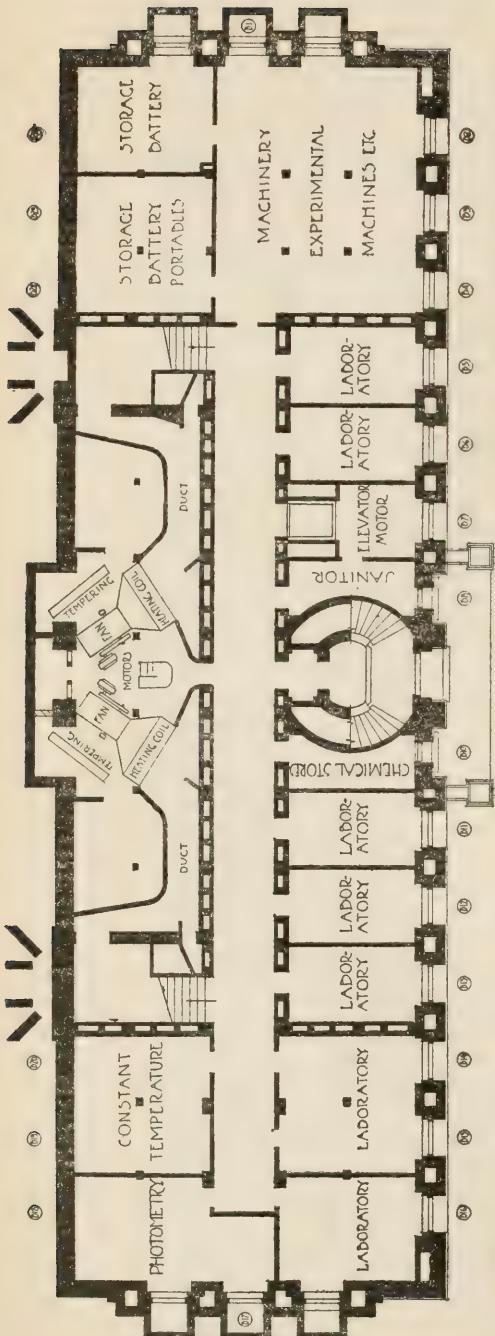
Besides the Department of Physics, the building houses the Department of Electrical Engineering, the Department of Graphic and Plastic Arts, and the Department of Mathematics. The rooms thus occupied are indicated on the plans with suitable letters in parentheses.

The plans show that the elementary work, the advanced undergraduate work, and the graduate work are, so far as possible, grouped separately. The elementary instruction is given on the second and third floors; the advanced undergraduate work is located on the first floor; and the graduate laboratories are in the lower part of the building.

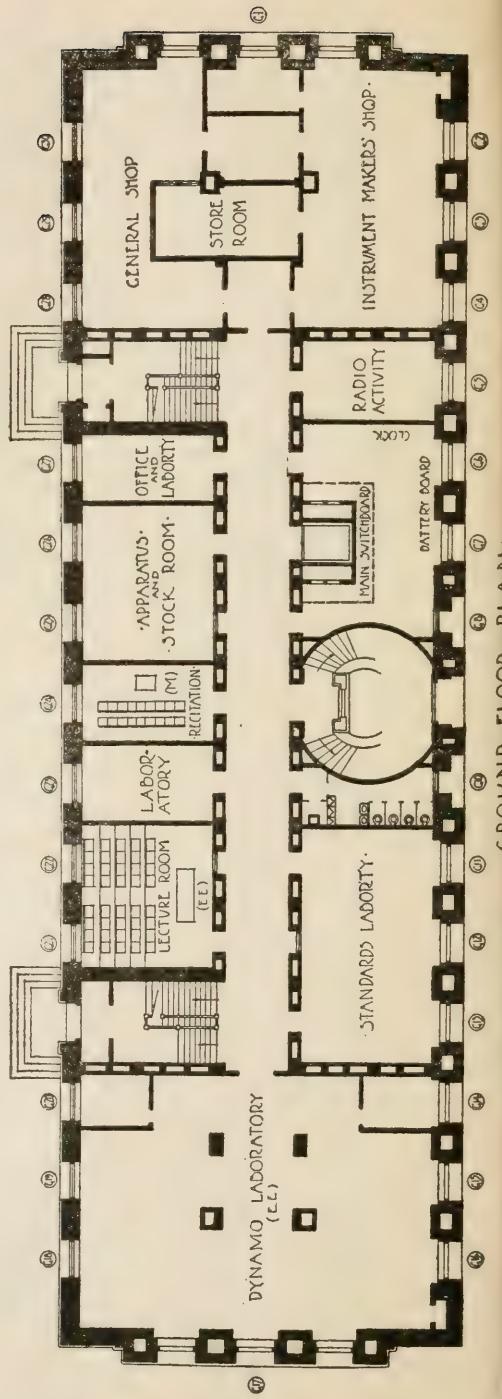
In each laboratory is stored the apparatus needed for that particular work. Aside from the lecture apparatus room, there is only one general apparatus storage room in the building. This, located in G 26, is used only by the instructional staff and the graduate students. The chemical stores are located conveniently to the research rooms.

The machinery in the Department is located at one end of the building.

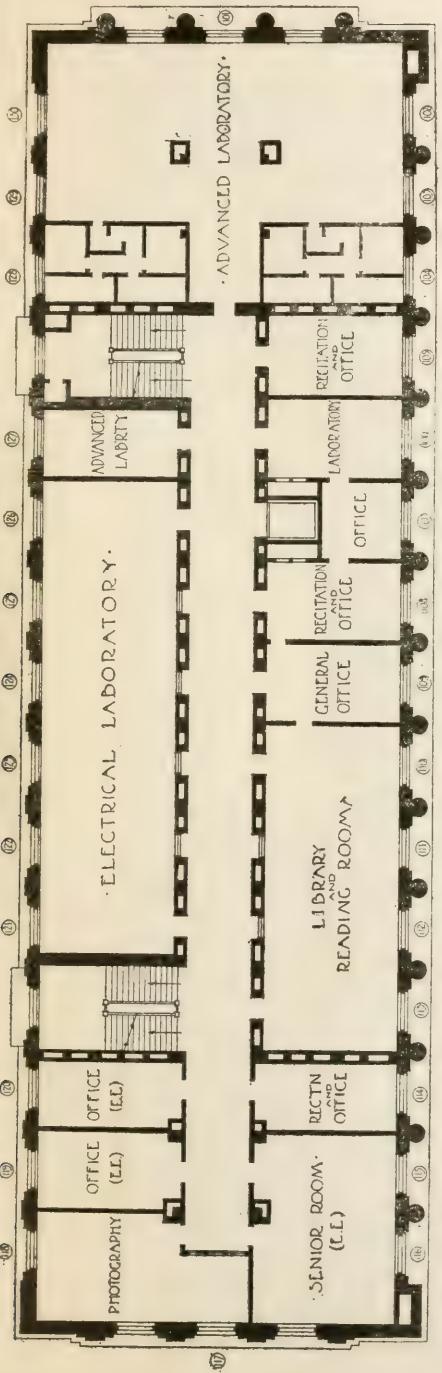
The general switchboard is located near the two shafts and is thus accessible from every part of the building.



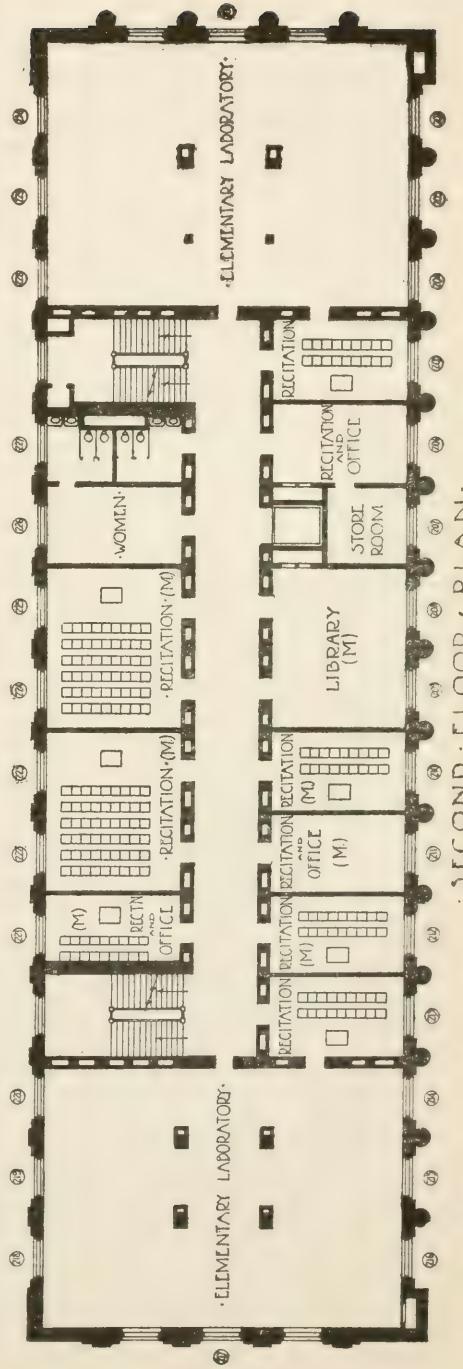
BASEMENT FLOOR PLAN.



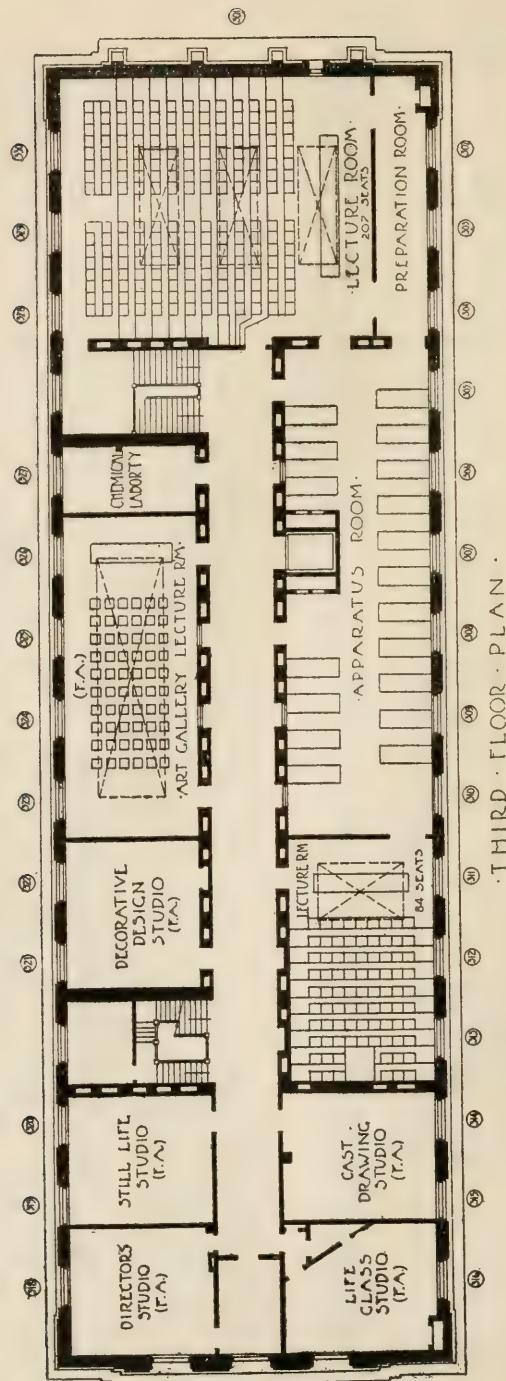
GROUND FLOOR PLAN.



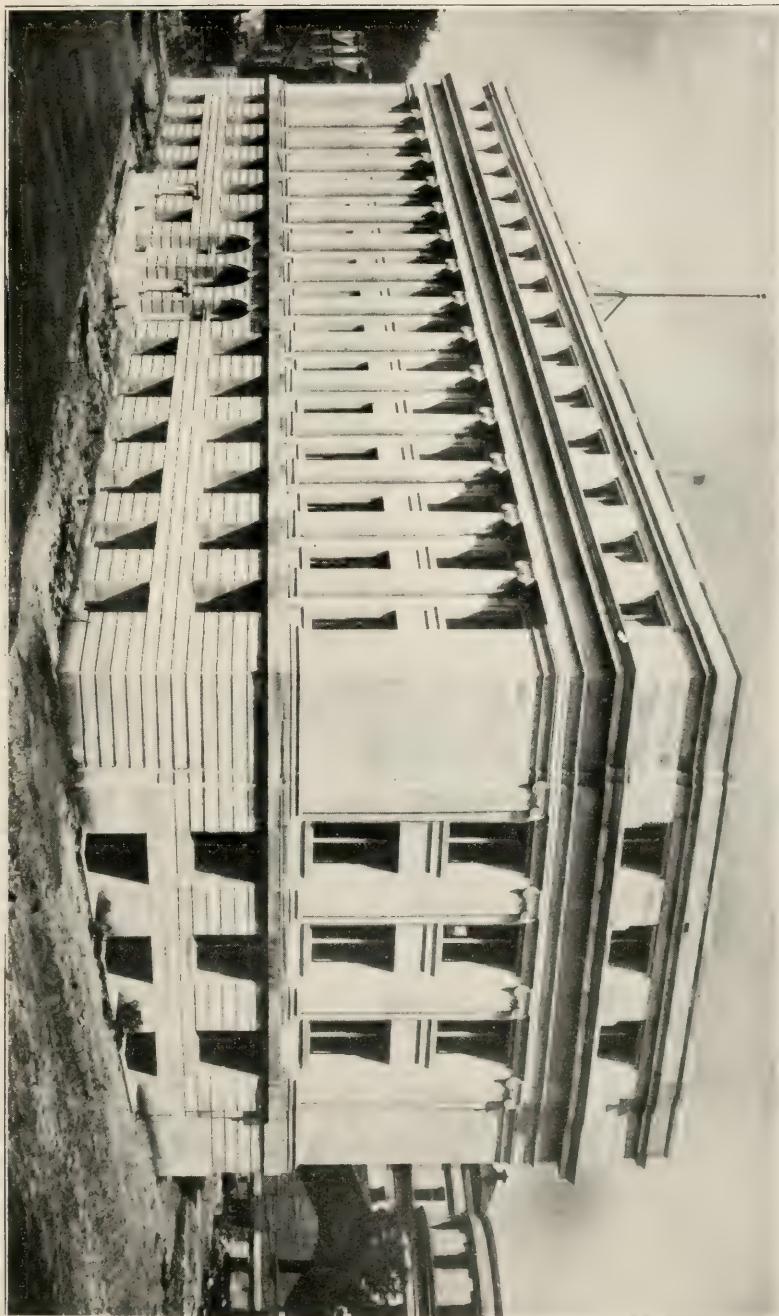
FIRST FLOOR PLAN.



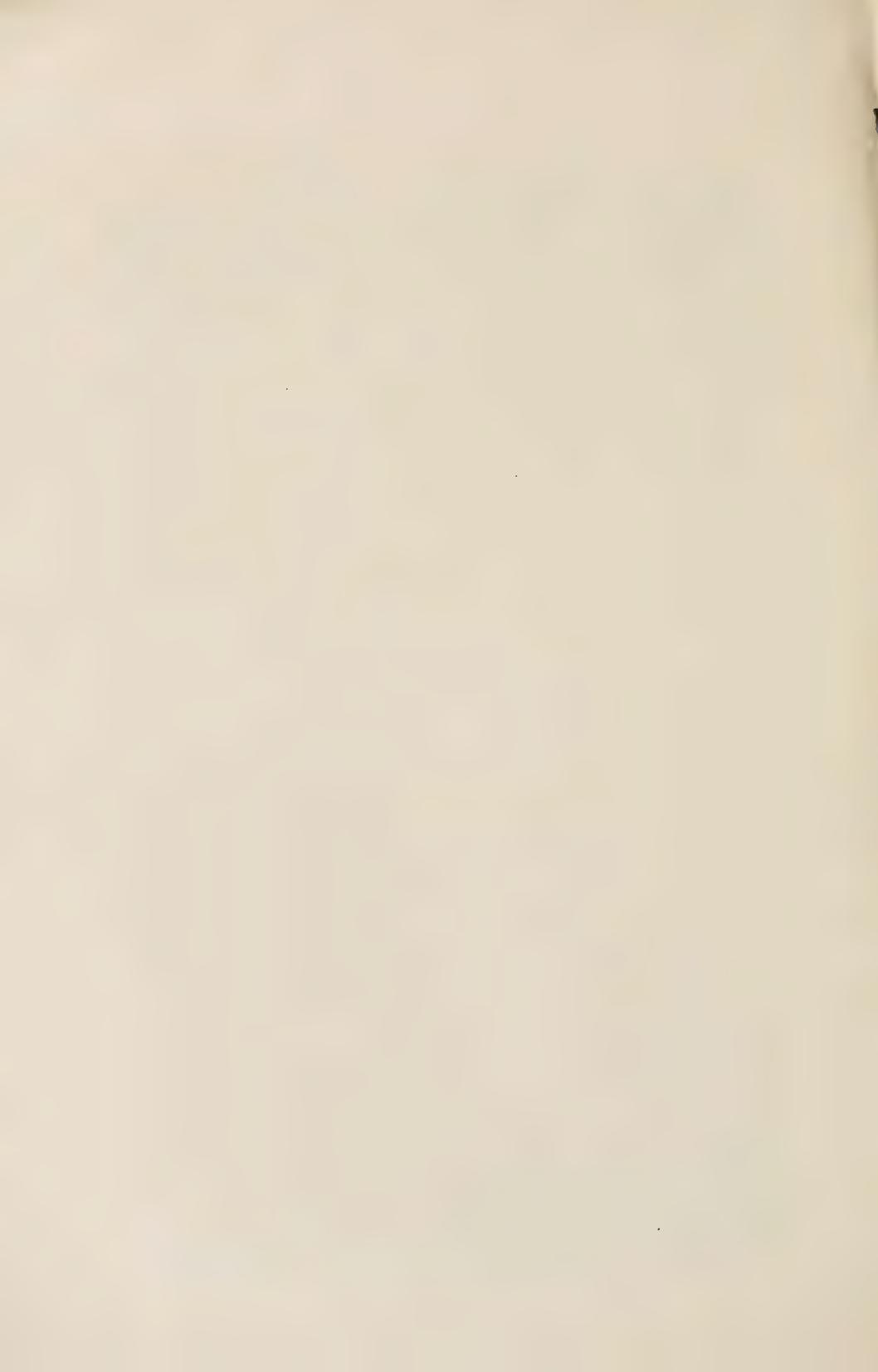
SECOND FLOOR PLAN.

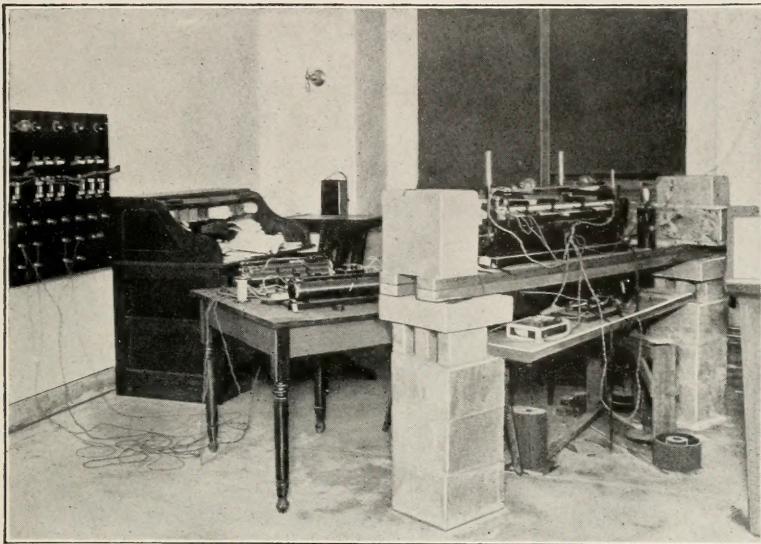


THIRD FLOOR PLAN.

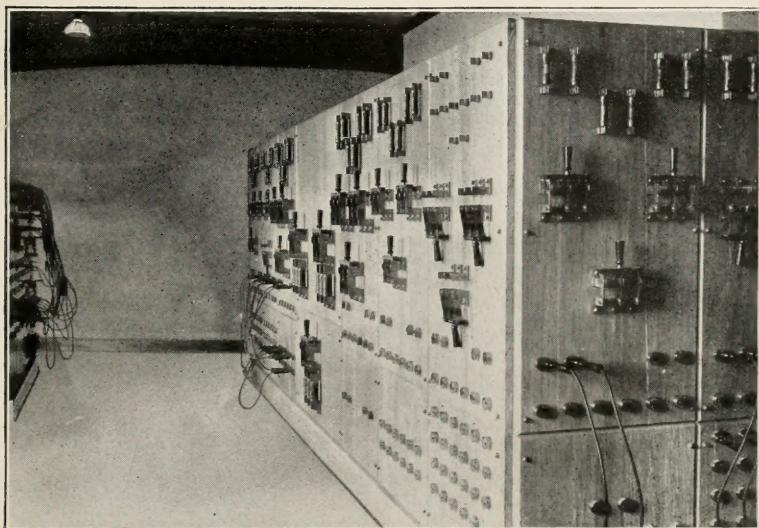


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